Integral model of noise-free radio communication lines

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The development of radio equipment, which can be the basis for radio lines, that can counteract various kinds of interference, both natural and artificial, has always been given special attention. In this case, the main way to interfere with such radio links is, as a rule, the expansion of the signal base. However, this method does not take into account the nature of the destructive effects in conditions of limited frequency and energy resources of radio channels. In this connection, the studies focused on the development of functional models of noise-free radio communication lines, taking into account the density of signal energy distribution in a limited state space, are relevant. This paper considers the development of an integrated model of noise-free radio communication lines, which is characterized by the accounting of statistical parameters of the radio channel model. The approaches to the estimation of efficiency of the developed functional model of the radio lines based on the calculation of information transmission reliability are presented. Theoretical solutions were obtained by the methods of statistical radio engineering and the theory of telecommunications; they are generalized for the models of channels with variable parameters in conditions of nonrandom destructive influence. A positive effect of the practical implementation of the developed model is shown on the basis of analytical modeling.

Keywords: noise immunity, integrated model, radio link, reliability

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Introduction

Achievements in modern science and technology allow the radio industry to develop and manufacture radio equipment with capabilities expanding remarkably the boundaries of implementation of operation modes of radio-frequency lines under complex signal and interference conditions. At the same time, the achievements characterized by the cognitive attributes based on the realization of network-centric control systems [1] stimulate the system of information warfare to search for new theoretical solutions for the realization of ravage methods which integrate the developed technologies for the software-defined radio system based on the solutions which are presented in the article [2].

The analysis of the innovation activity of the radio industry [3, 4] had shown that the most important scientific solutions were the algorithms for the realization of radio link business continuity methods including the conditions of premeditated ravage [5]. Generally, the capabilities of known methods for the synthesis of antijam radio systems are based on the significant extension of the signal base [6–8]; in most cases, these methods do not consider the type of ravages under the conditions of limited frequency and energy resources for radio channels. Another obvious disadvantage of known methods is the complexity of their aggregation at the designing stage for radio facilities based on the integrated theoretic platform.

At the same time, functional simulators of antijam radio links developed using alternative methods can be generated, particularly, using statistical radio engineering taking into account the density of signal energy at the limited space of states. This method determines the
relevance of solutions for a wide variety of tasks; the most desirable of such tasks is the development of a basic model for an antijam radio link and methods for evaluating its efficiency. The present article is devoted to the examination of these issues as one stage of the forthcoming investigation.

The description of a model for an antijam radio link

Let us assume a radio channel as a model characterized by the discontinuous communication with short-term and long-term fading (typical conditions for channels with ionospheric wave propagation), as well as with inhomogeneous conditions for the signal and jamming situation at operating frequencies [9, 10].

Let us determine the statistical characteristics of the considered radio links based on the distribution functions enveloping the signal and interference powers and determined by the laws of Rayleigh

\[
W(U_s) = \frac{2U_s}{U_{c,\exp}^2} \exp\left(-\frac{U_s^2}{U_{c,\exp}^2}\right),
\]

(1)

\[
W(U_n) = \frac{2U_n}{U_{n,\exp}^2} \exp\left(-\frac{U_n^2}{U_{n,\exp}^2}\right)
\]

(2)

and Rice

\[
W(U_s) = \frac{2U_s}{U_{c,\exp}^2} \exp\left(-\frac{U_s^2 + U_{c,\exp}^2}{U_{c,\exp}^2}\right) I_0\left(\frac{2U_s U_{c,\exp}}{U_{c,\exp}^2}\right),
\]

(3)

\[
W(U_n) = \frac{2U_n}{U_{n,\exp}^2} \exp\left(-\frac{U_n^2 + U_{n,\exp}^2}{U_{n,\exp}^2}\right) I_0\left(\frac{2U_n U_{n,\exp}}{U_{n,\exp}^2}\right),
\]

(4)

where \(U_s\), \(U_n\) are the signal and noise amplitudes, respectively; \(V\); \(U_{c,\exp}\), \(U_{n,\exp}\) are the effective values of voltage for the fluctuating signal and noise components, respectively, which are the parameters of distribution; \(V\); \(U_{c,\exp}\), \(U_{n,\exp}\) are the amplitudes of regular signal and noise components, respectively; \(V\); \(I_0\) is the zero-order Bessel function.

Let us assume that signal and noise phase fluctuation \(\varphi\) is characterized by the uniform distribution in the interval from 0 to \(2\pi\):

\[
W(\varphi) = \frac{1}{2\pi}.
\]

(5)

It should be noted that the selected distributions for the presented model of signals and noises exist in short time intervals (up to several minutes), within which the \(U_{c,\exp}\), \(U_{n,\exp}\) distribution parameters are invariable; and hence, the probabilistic and temporal parameters of radio links can be assumed as the constant. The distribution parameters of signals and noises in longer time intervals within the Rayleigh (Rice) laws are characterized by random variables with \(W(U_{c,\exp})\) and \(W(U_{n,\exp})\) probability densities, respectively.

Let us select the \(W(U_{c,\exp})\), \(W(U_{n,\exp})\) probability densities as logarithmic-normal distributed and express them in decibels [11]:

\[
W(y) = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(-\frac{(y - \bar{y})^2}{2\sigma_y^2}\right),
\]

(6)

\[
W(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left(-\frac{(x - \bar{x})^2}{2\sigma_x^2}\right),
\]

(7)

where \(\sigma_y\) and \(\sigma_x\), \(\bar{y}\) and \(\bar{x}\) are the mean-square deviations and mean values of signal and noise levels.

Let us select the error probability for signal element reception \(P_{\text{out}}\) and \(P_{\text{out}} < P_{\text{out,201}}\) distribution function as a parameter characterizing the fidelity of message transmission in the radio link; this will be done basing on the methods of statistical communication theory and taking into account the presented stochastic model of a radio channel described by formulas (6) and (7).

It should be noted that the assessment of fidelity for message transmission in the antijam radio link using the index of error probability for signal element reception \(P_{\text{out}}\) can be implemented only in relatively short time intervals, which has been mentioned earlier.

The values \(U_{c,\exp} / U_{n,\exp}(i = 1, 2, \ldots, m)\) in longer time intervals are described by random variables. So, the error probability for signal element reception in the radio link as the function of reduced random variables will be random, too. Further, it is necessary to rely on the methods of random variables and processes theory: the fidelity of message transmission in the radio link will be characterized by \(P_{\text{out}}\), the distribution function of a random variable will be determined by the probability of radio communication with fidelity no worse than specified by \(P_{\text{out}} < P_{\text{out,201}}\) [6, 12].

Let us select the method for the group use of frequencies [8] as the backbone for the development of models for antijam radio links; this will be done within the considered approach to the provision of the required efficiency for the radio link and taking into account the introduced system of indices and statistical distributions.

Let us present a functional model of radio links under the conditions of premeditated ravage (Fig. 1) based on the general theory of management.

The developed functional model summarizes the solutions proposed in the article [13]; herewith, the time intervals in this model are selected on the basis of the stationary state interval for the parameters of Rayleigh (Rice) distribution functions; so, the error probability for signal element reception in these intervals is constant.

The analysis time \(T\) is characterized by the invariance of parameters for the logarithmic-normal distribution law of \(U_{c,\exp}\) and \(U_{n,\exp}\) which determines the calculation period for the value \(P_{\text{out}} < P_{\text{out,201}}\) in the time-frequency matrix determining the functional model of the antijam radio link.
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**Figure 1. Functional model of the noise-free radio communication line:** 1 – frequency $f_n$ is used in the corresponding time interval $t_n-1-t_n$; 0 – frequency is not used.

| $0-t_1$ | $t_1-t_2$ | $\ldots$ | $t_{n-1}-t_n$ |
|---------|------------|-----------|---------------|
| $f_1$   | 1          | 1         | 0             | 1             |
| $f_2$   | 1          | 1         | 1             | 1             |
| $f_3$   | 0          | 1         | 1             | 1             |
| $\ldots$| $f_{n-1}$  | 1         | 0             | 0             |
| $f_n$   | 1          | 1         | 1             | 1             |

The feature of the model is that the alternate frequencies form the list of secondary frequencies. This allows the practical realization of the method for the group use of frequencies. Consequently, the developed functional model can provide the management for bandwidth-time resources of the radio link that is described by probabilistic and temporal characteristics (1)–(7).

The assessment of fidelity for message transmission in the integrated model of an antijam radio link

Let us implement the assessment of fidelity for information transfer for the confirmation of the legitimacy for the developed model. In this regard, it is necessary to introduce the term for the frequency utilization index in the antijam radio link.

The $i$-th frequency utilization index $\alpha_i$ can be interpreted as the ratio of the integrated time interval for frequency use in the radio link to the analysis period $T$, where the effective values of signals and noises levels are constant:

$$\alpha_i = \frac{\sum_{1}^{T} \alpha_i}{T}.$$  \hfill (8)

The coefficients $\alpha_i$ form the vector $A$, which determines the method of control for bandwidth-time resources:

$$A = \|\alpha_1 \alpha_2 \ldots \alpha_m\|.$$  \hfill (9)

Generally, the $A$ vector depends on the time:

$$A(t) = \|\alpha_1(t) \alpha_2(t) \ldots \alpha_m(t)\|.$$  \hfill (10)

Taking into account the developed integrated model of a radio link, it can be said that the value of probability for the error of signal element reception in the radio link does not depend on the vector for use of operating frequencies; it is determined by the parameters of statistical distributions and can be calculated as the arithmetic mean value of error probability at the operating frequencies. It should be noted that handling the problem of developing algorithms for the selection of operating frequencies from the formed secondary list is sufficiently important in these time intervals.

At the same time, the coefficient vector $A$ at the analysis interval $T$ determines the magnitude for the probability of radio communication with fidelity no worse than specified by $P_{\text{min}} \leq P_{\text{min, доп}}$. Let us develop the estimation technique for this index and introduce the following set of constraints. Let us assume that $m$ operating frequencies are allocated in the radio link for transmission of information. The processes of changing the excess of the signal level over the noise level $Z_i(t)$ ($i = 1, 2, \ldots, m$) in the analysis interval $T$ for each used frequency are normal independent...
The average duration of the inapplicable condition for the radio channel in the radio link, is the duration of the applicable condition for the radio channel at the frequency.

Let us approximate the changes in the state of the radio channel by time moments $t_k = kT$, where $k = 1, 2, \ldots$

Let us present the value of probability for radio communication with fidelity no worse than specified at the $i$-th operating frequency as follows [14]:

$$P_i(\alpha) = \lim_{T \to \infty} (P_i(S_m; f_{i}) + \alpha_i),$$

where $P_i(\alpha)$ is the probability of radio communication with fidelity no worse than specified at the $i$-th operating frequency $f_i$. Let us introduce the following notation system:

- $P_i(\alpha)$ is the probability of radio communication with fidelity no worse than specified at the $i$-th operating frequency $f_i$.
- $P_i(S_m; f_{i})$ is the probability of radio communication with fidelity no worse than specified at the $i$-th operating frequency $f_i$.
- $\alpha_i$ is the overrun tolerance of the signal level over the noise level determined on the basis of the methods described in the article [6].

Then, based on the equal significance of events described by the probabilities $P_i(\alpha)$ and $P_i(S_m; f_{i})$, and on the methods of radio communication operating frequency as follows:

$$P_i(\alpha) = \lim_{T \to \infty} (P_i(S_m; f_{i}) + \alpha_i).$$

Let us determine (12) after the transformation as follows:

$$P_i(\alpha) = \lim_{T \to \infty} \frac{T}{S_m + \alpha_i}.$$

The duration of the applicable condition for the radio channel at the frequency $f_i$ is the average duration of the applicable condition for the radio channel at the frequency $f_i$. Let us determine the prescribed value $T_i$ based on the methods of radio communication operating frequency as follows:

$$T_i = \frac{S_m}{\alpha_i}.$$
Let us extend the formula (16) for the case for ravage of interference with an invariant strategy.

In this context, it is possible to present the probabilities of radio communication with fidelity no worse than specified at each operating frequency as follows [8]

\[
P_{\text{int}}(P_{\text{out}} \leq P_{\text{out}}^*) = \frac{1}{\sqrt{2\pi} \sigma_{\text{out}}} \int_{-\infty}^{\infty} \exp\left(\frac{-(z_{\text{out}} - z)^2}{2\sigma_{\text{out}}^2}\right) f(z) \, dz,
\]

where \( P_{\text{out}}^* \) is the fixed value of error probability for signal element reception in the radio link in conditions for the simultaneous influence of inadvertent interference and jamming; \( z = \varphi^{-1}(P_{\text{out}}^* - z_{\text{out}}) \); \( \varphi^{-1} \) is the function inverse to \( \varphi(z, z_{\text{out}}) = P_{\text{out, int}}(z) \); \( f(z) \) is the probability integral determined according to the formula

\[
F(\xi) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\xi} e^{-\frac{t^2}{2}} \, dt.
\]

Fig. 2 shows the results of the calculation of probability for radio communication with fidelity no worse than specified in the developed integrated model of the radio link under the influence of noise jamming and the following initial data: \( m = 3 \), \( \xi_1 = 25 \text{ dB}, \xi_2 = 20 \text{ dB}, \xi_3 = 15 \text{ dB}, \xi_{1\text{mm}} = 20 \text{ dB}, \xi_{2\text{mm}} = 25 \text{ dB}, \xi_{3\text{mm}} = 30 \text{ dB}, \sigma_{\xi_1} = 5 \text{ dB}, \sigma_{\xi_2} = 8 \text{ dB}, \sigma_{\xi_3} = 7 \text{ dB}, \sigma_{\xi_{1\text{mm}}} = 3 \text{ dB}, \sigma_{\xi_{2\text{mm}}} = 5 \text{ dB}, \sigma_{\xi_{3\text{mm}}} = 6 \text{ dB} \), type of radio signal \(- F_{1-200}\).

The analysis of mathematical modeling results shows that the efficiency of the developed integrated model for antijam radio links depends significantly on the values of the vector \( A(t) \). In particular, the probability of radio communication with fidelity no worse than specified in the radio link rises from 0.55 to 0.72 with \( \alpha_1 = 1/20, \alpha_2 = 1/5, \alpha_3 = 3/4 \) and \( P_{\text{out}}^* = 0.05 \) in comparison with the uniform law of management \( \alpha_1 = \alpha_2 = \alpha_3 = 1/3 \).

**Conclusion**

The developed scientific and analytical tools formalize the problem of resources control in the antijam radio link; different models of radio channels and unrestricted types of signal structures are used for this task. In turn, this allows formulating the recommendations for specialists in the development of radio facilities at the stages for the synthesis of antijamming operation modes. The solution of these tasks receives special relevance during the development of transceivers based on the software defined radio. The authors connect the direction for future research with the development of timing cycles for resource management in the engineered integrated model of an antijam radio link.

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