

ВІЙСЬКОВА ТЕХНІКА І ТЕХНОЛОГІЇ ПОДВІЙНОГО ПРИЗНАЧЕННЯ

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CYCLIC THREE-STAGE PROCEDURE FOR SINGLE-CHANNEL DETECTION OF MOBILE RADIO SIGNALS IN THE FREQUENCY-TIME DOMAIN

In the context of a full-scale invasion and military operations for the independence of Ukraine, the issues of radio monitoring of radio emission sources of telecommunication networks and systems are gaining special attention and require fundamentally new approaches to the level of informatisation, technical implementation and increase of their efficiency.

Today, technical means of radio interception, monitoring and direction finding in mobile radio networks are implemented in the form of software and hardware complexes, the most important performance indicators of which are speed, detection accuracy and reliability of recognition of mobile radio communication means with their information content. At the same time, these issues still remain problematic and require further development of methods and means for searching and detecting signals of mobile radio communication equipment in both frequency and time environments of telecommunication channels and their subsequent information processing.

To address this issue, the authors propose a cyclic procedure for single-channel search for mobile radio signals with three stages of detection in the frequency-time domain and its mathematical model. It is shown that the use of a cyclic procedure for single-channel search for signals of mobile radio communication means with three stages of detection in the frequency-time domain will ensure high quality of radio monitoring and efficiency of estimation of spectral components of radio signals in terms of speed, detection accuracy and probability of recognition of mobile radio communication means with further determination of their information content.

Keywords: radio monitoring, telecommunication networks, mobile communication systems, performance indicators, speed, detection accuracy, recognition probability.

Introduction. In the context of a full-scale invasion and military operations for Ukraine's independence, the issues of efficiency of radio monitoring (RM) of radiation sources (RS) of information and telecommunication systems (ITS) are gaining special attention. This is confirmed by the fact that under martial law, the State Enterprise ‘Ukrainian State Centre of Radio Frequencies’ (SE ‘UCRF’), which in peacetime is responsible for radio frequency monitoring of fixed and mobile ITS, begins to be subordinated to the command of the General Staff of the Armed Forces of Ukraine, which ensures coordination of air defence, electronic and radar intelligence and electronic warfare of the state's security forces both in Ukraine and partially abroad.

Therefore, the issues related to the development of new and improvement of existing technical means of RM, based on the further development of the scientific and methodological apparatus, the results of assessing their effectiveness, software and algorithmic support and practical implementation, remain extremely relevant [1].

Problem formulation. Today, the technical means of radio interception, monitoring and direction finding in the networks of mobile radio communication systems are implemented in the form of software and hardware complexes (SHC), the most important performance indicators of

which are speed, accuracy of detection and probability of recognition of mobile radio communication means with their information content.

At the same time, these issues still remain problematic [2] and require further development of methods and techniques for searching and detecting signals of mobile radio communications in both frequency and time environments of telecommunication channels and their information processing.

Goal statement. In the structure SHC of the radio monitoring system for RS e main place is occupied by the subsystem of radio receiving devices (RRD), which solves the problem of signal detection in the frequency-time domain by cyclic procedures with one or more detection stages that implement methods of sequentially parallel signal search and detection. In [3, 4], a description of the cyclic procedure for single-channel of single-channel search for RM signals with one and two stages of detection in the form of a directed probabilistic graph, which is schematically shown in (Fig. 1), and its mathematical model in the form of expression (1) to determine the probability of successful

$$\begin{aligned}
 P_p(t) &= \frac{(1-D_1)(1-D_2)P_{\Pi}^t}{N} \times \\
 &\times \sum_{i=1}^N \sum_{n=0}^{\infty} \sum_{k=0}^n C_n^k (1-(1-D_1)P_{\Pi}^t)^k \times \\
 &\times \left[(1-D_1)P_p^t (1-(1-D_2)P_{\Pi}^t) \right]^{n-k} \times \\
 &\times \sum_{q=0}^{(N-1)n+(N-i)} C_{(N-1)n+(N-i)}^q (1-F_1)^q [F_1(1-F_2)]^{(N-1)n+(N-i)-q} \times \\
 &\times h \left[\begin{array}{l} t-t_{a1}(Nn+N-i+1) \\ -t_{a2}(Nn+N-i-q-k+1) \end{array} \right],
 \end{aligned} \tag{1}$$

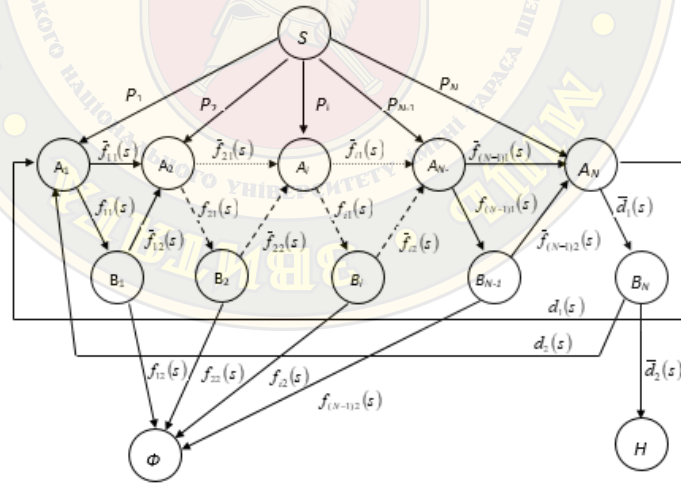


Figure 1 – Graph of the cyclic procedure of single-channel search with two stages of detection

where F_{q1}, F_{q2} are the probabilities of the first kind of error (false detection) when analysing a cell with number q ($q= 1, 2, \dots, N-1$) that does not contain a signal at the first and second detection stages;

D_1, D_2 - probability of the second type of error (signal miss) when analysing the cell with number N at the first and second detection stages;

P_i - he probability of starting viewing from the i -th cell ($i= 1, 2, \dots, N$).

According to the relation (1) in [4], the calculated dependences of the probability of successful completion of the search for a given time in the frequency-time domain on the search time for the case with one and two degrees of detection are given (Fig.2).

Analysis of the above data shows that the probability of successful completion of the search for the analysis time $t_a = 1$ sec is $P_1 = 0.341$ and $P_2 = 0.788$, respectively, with one and two detection levels, which requires further improvement of the search procedure in order to increase the probability and speed of successful completion of the detection of RS (search efficiency).

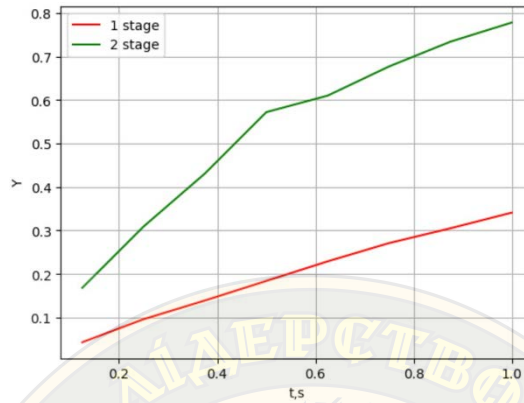


Figure 2 – Probability of successful completion of the search for a given time

Main part. To achieve this goal, a mathematical model of a single-channel search for signals of mobile radio communications with two stages of detection in the frequency-time domain was chosen as a prototype [4]. In contrast to the prototype, in the cyclic procedure with three stages of detection, the search for radio signals of the RS is carried out as follows. At the first stage, the signal is detected in each of the N analysed channels within the time t_{a1} which is less than the signal analysis time during the search with one detection stage. If a signal is detected, the second stage is activated for time t_{a2} . If a signal is detected at the second stage, the third stage starts to operate for time t_{a3} .

Thus, one of the conditions for a search with three stages of detection is the inequality $ta_2 < ta_2 < ta_3$. The search for a signal can be completed either on the first cycle (when the search area is first viewed) or after some random number of cycles, and the duration of each cycle is a random value due to the time spent analysing signals in the channels. The time taken to analyse the signal in each channel can have three values: t_{a1} , $t_{a1}+t_{a2}$ and $t_{a1}+t_{a2}+t_{a3}$.

According to the rules of graph transformation [5, 6], we obtained expressions for the functions of transition of a graph from the initial state S to the absorbing state H , which corresponds to the successful completion of the search (correct recognition):

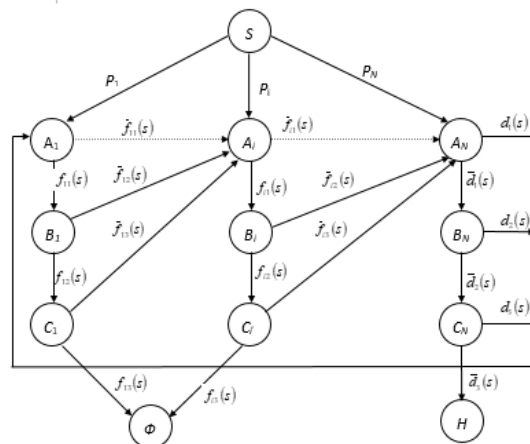


Figure 3 – Graph of a cyclic single-channel search procedure with three stages of detection.

$$H(s) = \frac{\bar{d}_1(s)\bar{d}_2(s)\bar{d}_3(s)\sum_{i=1}^N P_i \alpha}{1 - [d_1(s) + \bar{d}_1(s)d_2(s) + \bar{d}_1(s)\bar{d}_2(s)d_3(s)]\alpha}, \quad (2)$$

where:

$$\begin{aligned} \alpha &= \prod_{q=1}^{N-1} [1 - f_{q1}(s)f_{q2}(s)f_{q3}(s)], \\ d_1(s) &= D_1 e^{-t_{a1}s}, \quad d_2(s) = D_2 e^{-t_{a2}s}, \\ d_3(s) &= D_3 e^{-t_{a3}s}, \\ \bar{d}_1(s) &= (1 - D_1) e^{-t_{a1}s}, \quad \bar{d}_2(s) = (1 - D_2) e^{-t_{a2}s}, \\ \bar{d}_3(s) &= (1 - D_3) e^{-t_{a3}s}, \\ f_{q1}(s) &= F_{q1} e^{-t_{a1}s}, \quad f_{q2}(s) = F_{q2} e^{-t_{a2}s}, \\ f_{q3}(s) &= F_{q3} e^{-t_{a3}s} \end{aligned} \quad (3)$$

where F_{q1}, F_{q2}, F_{q3} are the probabilities of the first kind of error (false detection) when analysing a cell with number q ($q = 1, 2, \dots, N-1$) that does not hold the signal at the first, second and third detection stages;

D_1, D_2, D_3 - probabilities of the second kind of error (signal miss) when analysing a cell with number N at the first, second and third detection stages;

P_i - probability of starting viewing from the i -th cell ($i = 1, 2, \dots, N$).

Provided that the moments of signal appearance within the search area are uniformly distributed and that the search subsystem uses the same type of RRD,

$$F_{q1} = F_1, \quad F_{q2} = F_2, \quad F_{q3} = F_3$$

then after representing $H(s)$ as a geometric series and performing the inverse Laplace transform [5, 6], the expression for the probability of successful completion of the search for a given time in the frequency domain with three stages takes the form:

$$\begin{aligned} P_p^f(t) &= \frac{1}{N} \sum_{i=1}^N \sum_{n=0}^{\infty} \sum_r \frac{r!}{r_1! r_2! r_3!} (1 - D_1)(1 - D_2)(1 - D_3) \times D_1^r [(1 - D_1)D_2]^{r_2} [(1 - D_1)(1 - D_2)D_3]^{r_3} \times \\ &\times \sum_l \frac{l!}{l_1! l_2! l_3!} (1 - F_1)^{l_1} [F_1(1 - F_2)]^{l_2} [F_1 F_2(1 - F_3)]^{l_3} \times \\ &\times h \left[\begin{array}{l} t - t_{a1} \left(\sum_{v=1}^3 r_v + \sum_{v=1}^3 l_v + 1 \right) \\ - t_{a2} \left(\sum_{v=2}^3 r_v + \sum_{v=2}^3 l_v + 1 \right) - t_{a3} (r_3 + l_3 + 1) \end{array} \right] \end{aligned} \quad (4)$$

means \sum_l that you need to take the sum of different terms of the form

$$\frac{l!}{l_1!l_2!l_3!} a_1^{l_1} a_2^{l_2} a_3^{l_3};$$

r_1, r_2, r_3 - any integers or zeros whose sum is equal:

$$r = r_1 + r_2 + r_3 = n,$$

(5)

l_1, l_2, l_3 - arbitrary integers or zeros, the sum of which is defined as

$$l = l_1 + l_2 + l_3 = n(N-1) + N - i$$

(6)

To calculate the probability of successful completion of the search for a given time in the frequency domain with three degrees of detection, it is necessary for each i to sum all components with indices $n, r_1, r_2, r_3, l_1, l_2, l_3$, satisfying the inequalities:

$$\begin{aligned} & t_{a1} \left(\sum_{v=1}^3 r_v + \sum_{v=1}^3 l_v + 1 \right) + \\ & t_{a2} \left(\sum_{v=2}^3 r_v + \sum_{v=2}^3 l_v + 1 \right) \times \cdot \\ & + t_{a3} (r_3 + l_3 + 1) \leq t \end{aligned}$$

(7)

As with the search for RS signals with one and two detection stages, it is necessary to take into account, along with the frequency coincidence, the time coincidence in one channel of the desired signal.

The description of the state of a single-channel subsystem for searching for signals with three detection stages in the time domain is similar to the case of searching for signals with one and two stages [3,4]. But the time spent on analysing a signal in one channel will already have three values: t_{a1} in the case when only the first stage is involved, $t_{a1} + t_{a2}$ in the case when two stages are involved, and $t_{a1} + t_{a2} + t_{a3}$ in the case when three detection stages are involved. The time of channel analysis when a signal is detected is equal to the sum of $t_{a1} + t_{a2} + t_{a3}$. Taking this into account, the time of one search cycle T is defined as

$$\begin{aligned} T = & t_{a1}N + t_{a2}(1 - D_1 + (N-1)F_1) + \\ & + t_{a3}[(1 - D_1)(1 - D_2) + (N-1)F_1F_2]. \end{aligned}$$

(8)

To calculate the probability of an RRD and a signal meeting during the time t_a of analysing N channels, we use the basic provisions of the theory of geometric probabilities similar to the case of a search with a single detection stage [5, 6]. Then the time of signal analysis in one channel t_a is

$$\begin{aligned} t_a = & \frac{T}{N} = t_{a1} + t_{a2} \frac{1 - D_1 + (N-1)F_1}{N} + \\ & + t_{a3} \frac{(1 - D_1)(1 - D_2) + (N-1)F_1F_2}{N} \end{aligned}$$

(9)

Taking into account the above, the expression for calculating the probability of successful completion of a search with three degrees of detection in the time domain in one viewing cycle will be as follows:

$$P_p^t = \frac{N(\tau_c - t_{a1}) - t_{a2}(1 - D_1 + (N - 1)F_1) - t_{a3}[(1 - D_1)(1 - D_2) + (N - 1)F_1F_2]}{N \left[\tau_c + Nt_{a1} + t_{a2}(1 - D_1 + (N - 1)F_1) + t_{a3}[(1 - D_1)(1 - D_2) + (N - 1)F_1F_2] \right]} \quad (10)$$

The fact of simultaneous detection of a signal in the frequency and time domains of the search can be considered as independent random events. Then the expression for determining the probability of successful completion of the search for a given time in the frequency-time domain with three degrees of detection can be as follows:

$$P_p(t) = \frac{1}{N} \sum_{i=1}^N \sum_{n=0}^{\infty} \sum_r \frac{r!}{r_1!r_2!r_3!} \times (1 - D_1)(1 - D_2)(1 - D_3) P_p^{t^3} \times \left[1 - (1 - D_1)P_p^t \right]^n \left[(1 - D_1)P_p^t (1 - (1 - D_2)P_p^t) \right]^{r_2} \times \left[(1 - D_1)(1 - D_2)P_p^{t^2} (1 - (1 - D_3)P_p^t) \right]^{r_3} \times \sum_l \frac{l!}{l_1!l_2!l_3!} (1 - F_1)^{l_1} [F_1(1 - F_2)]^{l_2} [F_1F_2(1 - F_3)]^{l_3} \times h \left[\begin{array}{l} t - t_{a1} \left(\sum_{v=1}^3 r_v + \sum_{v=1}^3 l_v + 1 \right) - \\ t_{a2} \left(\sum_{v=2}^3 r_v + \sum_{v=2}^3 l_v + 1 \right) - t_{a3}(r_3 + l_3 + 1) \end{array} \right] \quad (11)$$

To calculate the probability of successful completion of the search for a given time in the frequency-time domain with three stages in expression (11), it is necessary for each i to sum all the components with indices $n, r_1, r_2, r_3, l_1, l_2, l_3$, satisfying inequalities (7).

Thus, the cyclic procedure for searching for RS for a given time in the frequency-time domain with three stages is mathematically described.

To evaluate the effectiveness of the considered procedure, the dependences of the probability of successful completion of the search for a given time in the frequency-time domain on the search time for cases with one, two, and three stages of detection were calculated and plotted against the search time (Fig. 3).

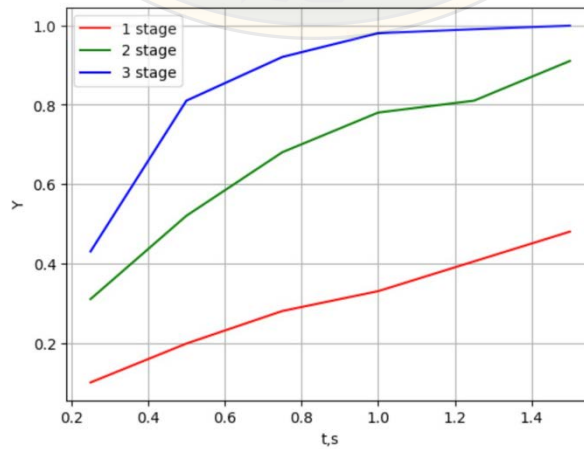


Figure 4 – Dependence of the probability of successful completion of the search for a given time in the frequency-time domain on the search time with different number of detection degrees

When constructing these dependencies, the following were assumed: $\tau_c = 100$ ms, $F_1 = F_2 = F_3 = 0.001$, $N = 8$, the analysis time at each subsequent detection stage is 3 times longer than at the previous one. The total signal analysis time at all detection stages is $t_a = 40$ ms. The probability of a signal miss at the last stage was taken as $P = 0.1$.

The probability of signal miss at the previous stages was determined by the Neumann-Pearson criterion [5,6] at the given values of the probability of false detection. It is taken into account that the detection parameter (signal-to-noise ratio) is inversely proportional to the duration of signal analysis [7], and the signal is detected with a random amplitude and phase.

Conclusions. The analysis of the obtained results shows that in order to increase the efficiency of searching for RS signals, it is advisable to use cyclic search procedures with several stages - multistage detection. The use of the procedure for searching for RSI with one stage of detection is inefficient, but the time required to successfully complete the search is minimal. The introduction of the second stage makes it possible to significantly increase the probability of successful completion of the search for a given time by an average of 2.5 times compared to the search with one stage of detection, and can be recommended for use in practice. The use of a cyclic procedure for detecting RS with three stages further increases the probability of successful completion of the search within a given time by 1.3 times compared to the search with two stages of detection. In this case, this probability tends to one, which suggests that further increase in the number of stages becomes inappropriate.

In addition, it is possible to increase the probability and reduce the average time of successful completion of the search for RSI by parallel operation of several RFPs, each of which performs an independent cyclic signal search. That is, there is a scientific and practical task to consider the procedures of multichannel (sequentially parallel) search for RSI and determine the rationally required number of RFPs, which makes it possible to ensure the required probability of successful completion of the signal search for a given time. However, these issues are beyond the scope of this article, require separate analysis and can be considered as areas for further research.

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ЦИКЛІЧНА ТРИЕТАПНА ПРОЦЕДУРА ОДНОКАНАЛЬНОГО ВИЯВЛЕННЯ РУХОМИХ РАДІОСИГНАЛІВ У ЧАСТОТНО-ЧАСОВІЙ ОБЛАСТІ

В умовах повномасштабного вторгнення та військових дій за незалежність України питання радіомоніторингу джерел радіовипромінювання телекомунікаційних мереж і систем набувають особливої уваги та потребують принципово нових підходів до рівня інформатизації, технічної реалізації та підвищення їх ефективності.

На сьогодні технічні засоби радіоперехоплення, моніторингу та пеленгування в мережах рухомого радіозв'язку реалізуються у вигляді програмно-апаратних комплексів, найважливішими показниками ефективності яких є швидкодія, точність виявлення та достовірність розпізнавання засобів рухомого радіозв'язку з їх інформаційним наповненням. Разом з тим, ці питання все ще залишаються проблемними і потребують подальшого розвитку методів і засобів пошуку та виявлення сигналів засобів рухомого радіозв'язку як у частотному, так і в часовому середовищах телекомунікаційних каналів зв'язку та їх подальшої інформаційної обробки.

Для вирішення цієї проблеми запропоновано циклічну процедуру одноканального пошуку сигналів рухомого радіозв'язку з трьома етапами виявлення в частотно-часовій області та її математичну модель. Показано, що використання циклічної процедури одноканального пошуку сигналів рухомих засобів радіозв'язку з трьома етапами виявлення в частотно-часовій області забезпечить високу якість радіомоніторингу та ефективність оцінювання спектральних складових радіосигналів за показниками швидкості, точності виявлення та ймовірності розпізнавання рухомих засобів радіозв'язку з подальшим визначенням їх інформаційного змісту.

Ключові слова: радіомоніторинг, телекомунікаційні мережі, системи мобільного зв'язку, показники ефективності, швидкість, точність виявлення, вірогідність розпізнавання.

