Software and hardware complexes for multistage monitoring of mobile radio signals and features of their operating modes

Anatolii Ilnytskyi[1], Oleg Tsukanov[2], Olha Marchuk[3]

[1,2]National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute" 37 Beresteysky Avenue, Kyiv, Ukraine, 03056
[3]State University of Information and Communication Technologies
[1]anatolii.ilnytskyi@gmail.com, https://orcid.org/0000-0003-0454-1819
[2]cukanov-o@ukr.net, https://orcid.org/0000-00027104-3274
[3]olya.marchuk.1999@ukr.net

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Abstract Today, technical means of radio interception, monitoring and direction finding in mobile radio communication networks are implemented in the form of software and hardware complexes, the most important performance indicators of which are considered to be speed, detection accuracy and probability of recognition of mobile radio communication means with their information content. However, the effectiveness of these complexes still remains problematic and requires 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 subsequent information processing.
To solve this problematic issue, the authors consider a typical variant of the structural scheme of the software and hardware complex for searching and detecting signals and the peculiarities of applying the procedures for multi-stage search and detection of signals in radio monitoring of radio sources of mobile communication systems. It is shown that software and hardware systems can have several modes of operation depending on the type of control channel.
The article also presents the results of calculations of the probability of successful completion of the search for a signal of a distributed control channel of mobile radio communications for a given time with three stages of detection in the frequency-time domain with one radio receiving device at a different number of empty channels (p = 1, 5, 9) in one search cycle. It is shown thatadditional estimation of the input signal level by the radio receiving device at the first stage of detection increases the search efficiency with an increase in the number of empty channels.

Anatolii Ilnytskyi
Associate Professor, PhD, the Departmen of Information technologies in telecommunications

Oleg Tsukanov
Associate Professor, PhD, the Departmen of Information technologies in telecommunications

Olha Marchuk
Postgrad Program, Dept. of Telecom Systems & Networks

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INTRODUCTION

Modern telecommunication networks (TCN) are the integration of analogue public switched telephone systems, digital telephone networks, cellular and satellite communication systems, and data transmission systems to provide a global information and telecommunication space. Public telecommunication systems are characterised by the use of a large number of objects and radio frequency sources (RS) with the most modern and diverse protocols for data transmission, protection and concealment of information. Reducing the structural and information availability of mobile radio communication systems (MRC) is ensured by the use of automated information transmission systems with automatic selection of the operating frequency of signals, the diversity of MRC, and the complication of frequency and time access.

It is known [1,2] that the main channels that form a single global TCN are zonal, regional and trunk networks built on the basis of radio, radio relay, satellite, fibre-optic and wire (cable) communication lines. At the same time, the monitoring of both general and military MRC is of particular interest. This requires the development and use of very sophisticated technical means of their radio monitoring (RM). Therefore, the relevance of the topic and the results of the study, which consider the peculiarities of applying the procedures of multi-stage search and detection of signals in the radio monitoring of mobile communication systems by software and hardware complexes (SHC), is beyond doubt.

PROBLEM FORMULATION

The analysis of recent research and publications shows that a large number of scientific papers and publications, including those of the authors of this article, are devoted to the problem of radio monitoring of both fixed and mobile communication systems [3,4,5]. These scientific papers theoretically cover problematic issues of radio monitoring of TCN sources and objects and a general scientific conceptual approach to their solution; cyclic multi-stage procedures for single-channel search and detection of MRC signals in the frequency-time domain; mathematical models of single-channel search and detection of signals with one, two and three stages of detection in radio frequency monitoring of mobile communication TCN;

synthesis of SHC for search, detection and demodulation and identification of MRCS signals with frequency manipulation, etc.

However, the problematic issues of synthesis and practical implementation of the SHC for searching and detecting MRC signals and the peculiarities of their operating modes remained unaddressed by the authors.

GOAL STATEMENT

Therefore, the purpose and main content of the article is to consider the features of multi-stage monitoring of mobile radio signals by software and hardware complexes. The object of research here is the process of multi-stage search and detection of mobile radio communications signals, and the subject of research is the peculiarities of the operating modes of software and hardware complexes when implementing cyclic procedures for multi-stage search and detection of signals, where the procedure is understood as a system of formalised rules for collecting, processing and analysing information to solve a given scientific task and obtain new knowledge.

MAIN PART

As noted in [6], in the radio monitoring of SHC using a multi-stage method of searching and detecting signals, SHCs are used, a simplified block diagram of which is shown in Fig. 1, consisting of: an antenna system (AS); a set of radio receiving devices (〖RRD〗_1, 〖RRD〗_2…, 〖RRD〗_N) for sequential parallel signal search; a signal demodulation unit (DM); a signal division device for spectral components (SDDS); a set of single-tone (STS) and multi-tone signal recognition units (MSRU); a signal registration unit (RS); a control and decision unit (CDU).

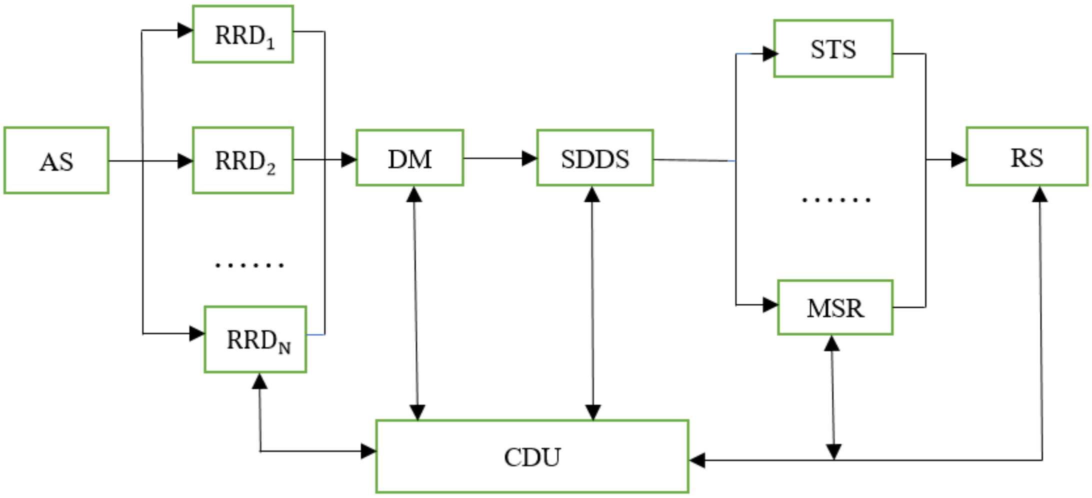

Fig.1. Block diagram of the software and hardware complex

This SHC solves the problem of searching, detecting, recognising and identifying signals in the time-frequency domain using cyclic procedures with one or more detection stages that implement sequential-parallel search methods described by well-known mathematical models [3,4,5] based on the theory of directed probability graphs. At the same time, SHC can have both dedicated and distributed control channels. Thus, only control signals are transmitted in dedicated channels, and they do not change their location for a long time, so the search for these channels does not cause difficulties. At the same time, distributed control channels differ from dedicated channels in that they exist only until the start of broadcasting, which is transmitted over the same channels.

When searching for and detecting dedicated control channels, where only control signals are transmitted, the search time does not play a significant role due to the constancy of such channels in the frequency-time domain. That is, to organise the search for a dedicated channel, it is enough to use a simple cyclic sequential search with one detection stage and even with one RRD and the corresponding operating mode.

Taking this into account, when analysing a channel that does not contain a signal, the probability of detection error (of the first kind) can be assumed to be zero F = 0. Then the formula for calculating the probability of successful completion of a search with one degree of detection in the time-frequency domain by one RDD can be given in a well-known form [3], which does not require explanation and commentary:

$$P_{\Pi}(t)=\frac{(\tau_c-t_a)(1-D)}{N(\tau_c+Nt_a)}\sum_{i=1}^{N}\sum_{n=0}^{\infty}\left(1-\frac{(\tau_c-t_a)(1-D)}{\tau_c+Nt_a}\right)^{n}\times\times h\left[t-(Nn+N-i+1)\ t_a\right] \qquad (1)$$

In practice, the following situations are possible when organising the search for MRC signals with a distributed control channel

there is no signal in the channel (the channel is empty);

a speech signal is present in the channel;

a digital signal is present in the channel, but not a control channel signal;

a control signal is present in the channel.

In all of these situations, except the last one, it is necessary to continue searching and analysing signals using the sequential-parallel method with three detection stages and different signal analysis times at each stage. That is, a change in the situation during the signal search affects the change in the SHC operating mode and its features.

For example, the use of scanning RRDs in SHC, which are capable of evaluating and transmitting the input signal level to the control unit [6], makes it possible to significantly reduce the time for analysing empty channels. With this in mind, the first stage must ensure energy availability and switch to the second stage of detection when the signal level exceeds the specified detection threshold. It is worth noting that when searching for a signal in (N-1) channels, the transition from the first detection stage to the second is possible even in the absence of the desired service channel signal, but in the presence of a broadcast channel. Then it can be assumed that the probability of the first kind of error at the first detection stage in an empty channel F1 = 0, and in the presence of a speech signal in the channel F1 = 1. Since the presence of a speech signal in MRC channels is random, it is proposed to introduce an auxiliary coefficient p to analyse this situation, equal to the number of empty channels among the (N-1) analysed in one search cycle. Then the average probability of the first kind of error at the first stage of detection Fser will be defined as

$$F_{ser} = 1- \frac{p}{N-1} \quad (2)$$

At the second stage, it is necessary to determine whether the signal is digital, i.e. a stream of bits. However, the digital stream in the SHC structure (Fig. 1) is formed in the signal demodulation subsystem, i.e. after their search. Therefore, it is necessary to provide feedback from the signal demodulation subsystem to the signal search subsystem through the control unit, which transmits information about whether the received signal is digital. To perform such an assessment, it is proposed to use the total value of bit synchronisation errors at a given interval during signal demodulation [7]. Here, the bit synchronisation errors Eb are calculated at the moments when the demodulated signal transitions from 1 to 0 or vice versa (Fig. 2) and are numerically equal to the remainder of the division of the number of samples accumulated since the previous calculation of the error nprev by the number of samples per bit nbit:

$$E_b = n_{\text{prev}} \bmod n_{\text{bit}} \quad (3)$$

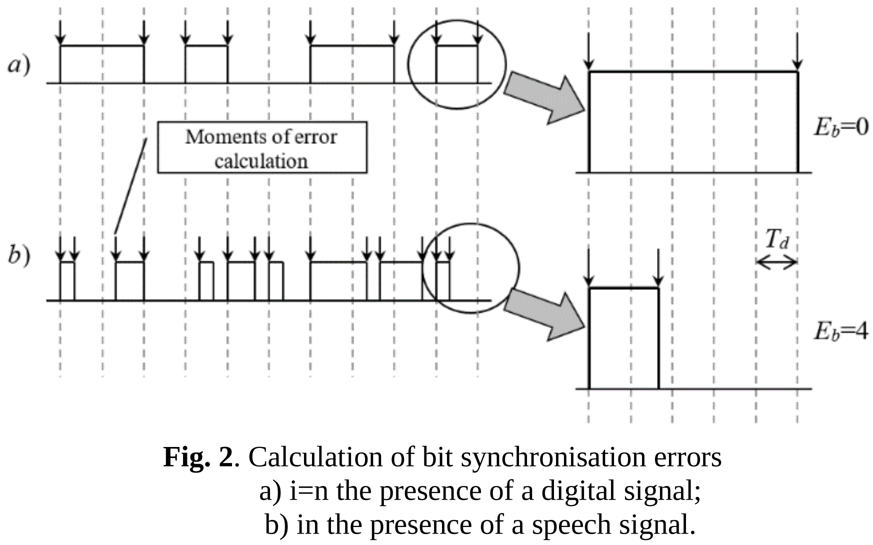

Fig. 2. Calculation of bit synchronisation errors
a) i=n the presence of a digital signal;
b) in the presence of a speech signal.

The interval between neighbouring samples is equal to the sampling period of the input signal Td. Due to the fact that in the process of demodulation, the transmission rate of digital MRC signals is known, the bit synchronisation error can be neglected (Fig.2.a). However, during the demodulation of a speech signal, the moments of sign change in the demodulated signal will be random and, therefore, the bit synchronisation error will be different from zero.

To obtain a more accurate estimate of the bit synchronisation error, it is necessary to average the obtained error values over a certain time interval and compare the obtained values with a specified threshold. Since the information about this error is transmitted to the second detection stage, to ensure search efficiency, it is necessary that the selected time interval is longer than the signal analysis time at the first detection stage and shorter than the analysis time at the third stage. With this approach, the probability of detection error (of the first kind) of the control channel service signal at the second detection stage can be assumed to be equal to F2 = 0.

At the third stage, the digital signal of the desired MRC control channel is detected, similar to the case when searching for a dedicated channel described above. At the same time, the probability of detection error (of the first kind) at the third detection stage is assumed to be equal to F3 = 0.

Based on the foregoing and taking into account (2), the well-known formula given in [5] for calculating the probability of successful completion of the search for a distributed control channel signal for a given time with three detection stages in the frequency-time domain by one RRD takes the following form:

$$P_{\Pi}(t)=\frac{1}{N}\sum_{i=1}^{N}\sum_{n=0}^{\infty}\sum_{r}\frac{r!}{r_1!r_2!r_3!}(1-D_1)(1-D_2)(1-D_3)P_{\Pi}^{t\,3}\times$$
$$\times\left[1-(1-D_1)P_{\Pi}^{t}\right]^{r_1}\left[(1-D_1)P_{\Pi}^{t}\left(1-(1-D_2)P_{\Pi}^{t}\right)\right]^{r_2}\times$$
$$\times\left[(1-D_1)(1-D_2)P_{\Pi}^{t\,2}\left(1-(1-D_3)P_{\Pi}^{t}\right)\right]^{r_3}\times$$
$$\times\sum_{q=0}^{(N-1)n+(N-i)}C_{(N-1)n+(N-i)}^{q}\left(\frac{p}{N-1}\right)^{q}\times$$
$$\times\left(1-\frac{p}{N-1}\right)^{(N-1)n+(N-i)-q}\times$$
$$\times h\begin{bmatrix}t-t_{a1}(Nn+N-i+1)-\\ t_{a2}(Nn+N-i-q-r_1+1)-t_{a3}r_3\end{bmatrix} \quad (4)$$

where P_{p}^{t} - the probability of successful signal detection in the time domain, determined by the expression:

$$P_{\Pi}^{t}=\frac{\begin{matrix}N(\tau_c-t_{a1})-\\ -t_{a2}(N-p-D_1)-\\ -t_{a3}(1-D_1)(1-D_2)\end{matrix}}{N\begin{bmatrix}\tau_c+Nt_{a1}+\\ +t_{a2}(N-p-D_1)+\\ +t_{a3}(1-D_1)(1-D_2)\end{bmatrix}} \quad (5)$$

It should be noted that in expressions (4) and (5), unlike in [5], the following additional notations are used:

p - the number of empty channels among N-1 analysed in one search cycle;

D1, D2, D3 - the probabilities of the second kind of error (signal miss) when analysing a cell with number N at the first, second, and third detection stages;

$\sum_{l}$ means that it is necessary to take the sum of different terms of the form

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

r1, r2, r3 - any integers or zeros, the sum of which is equal to:

$$r=r_1+r_2+r_3=n \quad (6)$$

l1, l2, l3 - any integers or zeros, the sum of which is defined as

l = l_1 + l_2 + l_3 = n(N-1) +N – i(7)

To calculate the probability of successful completion of the search for a signal of a distributed control channel for a given time, it is necessary to sum all the components with indices n, r1, r2, r3, q satisfying the inequalities using expression (4) for each i:

$$t_{a1}\left(Nn+N-i+1\right)+ \\ t_{a2}\left(Nn+N-i-q-r_1+1\right)+t_{a3}r_3 \le t \quad (8)$$

Thus, according to expression (4), we calculated (Table 1) and plotted (Fig. 3) the dependences of the probability of successful completion of the search for the signal of the distributed MRC control channel for a given time with three degrees of detection in the frequency-time domain by one RRD at a different number of empty channels (p = 1, 5, 9) in one search cycle.

Table 1.
Probabilities of successful completion of the search for a given time

***t*, s**	0,1	0,2	0,3	04	0,5	0,6
***p* = 1**	**0,097**	**0,19**	**0,22**	**0,3**	**0,38**	**0,41**
***p* = 5**	**0,2**	**0,38**	**0,5**	**0,6**	**0,68**	**0,7**
***p* = 9**	**0,58**	**0,8**	**0,92**	**0,98**	**0,99**	**0,999**

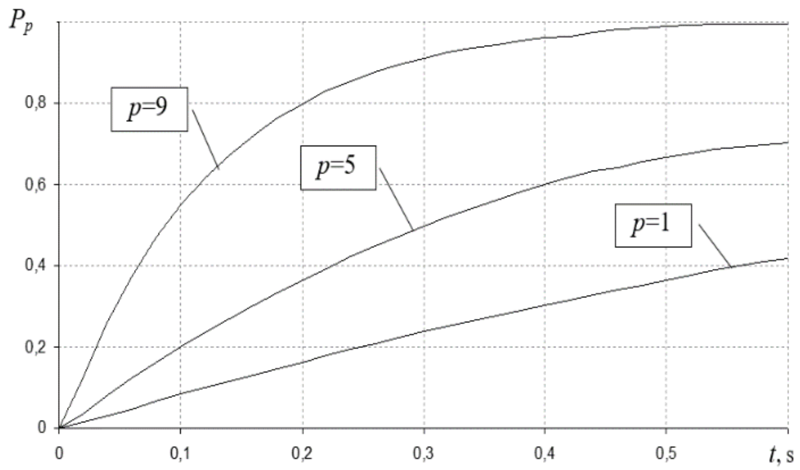

Fig. 3. Dependences of the probability of successful completion of the search for the signal of the distributed control channel of the MRC for a given time at a different number of empty channels (p = 1, 5, 9)

The graphical dependence and numerical data show that by estimating the level of the RRD input signal at the first detection stage, the detection efficiency increases with an increase in the number of empty channels.

Thus, the features of the SHC operating modes with a dedicated and distributed control channel have been described quite fully. But in practice, some MRC do not have control channels. In this case, a signal indicating the start of broadcasting is transmitted immediately before the start of the communication session. To organize the search for such signals, it is proposed to use a sequential-parallel search with two stages of detection: at the first stage, the signal whose energy exceeds the threshold specified in the RRD is detected; at the second stage, the signal that is a sign of the start of broadcasting is detected.

As in the mode of searching for signals of the MRC with a distributed control channel, it should be noted that when searching for a signal in (N-1) channels, the transition from the first stage of detection to the second is possible even in the absence of the desired signal (a sign of the beginning of broadcasting), but in the presence of a speech signal. In this case, we can assume that the probability of a first-order error at the first stage in an empty channel is F1= 0, and in the presence of a speech signal in the channel, F1= 1. That is, the average probability of a first-order error (2) at the first detection stage will be determined as

$$F_1 = 1 - \frac{p}{N-1}$$

with an increase in the number of empty channels p >> 1 tends to zero.

Taking this into account, the formula for calculating the probability of successful completion of a search with two detection stages in the time-frequency domain by one RFI can be written as follows:

$$P_{\text{p}}(t) = \frac{(1-D_1)(1-D_2){P_{\text{p}}^{t}}^{2}}{N}\sum_{i=1}^{N}\sum_{n=0}^{\infty}\sum_{k=0}^{n} C_n^k \left(1-(1-D_1)P_{\text{p}}^t\right)^k \times \times \left[(1-D_1)P_{\text{p}}^t\left(1-(1-D_2)P_{\text{p}}^t\right)\right]^{n-k} \times \times \sum_{q=0}^{(N-1)n+(N-i)} C^q_{(N-1)n+(N-i)}\left(\frac{p}{N-1}\right)^q \times \left[\left(1-\frac{p}{N-1}\right)(1-F_2)\right]^{(N-1)n+(N-i)-q} \times \times h\left[\begin{matrix} t - t_{a1}(Nn+N-i+1) - \\ -t_{a2}(Nn+N-i-q-k+1)\end{matrix}\right], \quad (9)$$

where p -the number of empty channels among N-1 analysed in one search cycle;

- the probability of successful signal detection in the time domain, which, taking into account (2), is defined as

$$P_{\text{p}}^t = \frac{N(\tau_c - t_{a1}) - t_{a2}(N-p-D_1)}{N\left[\tau_c + Nt_{a1} + t_{a2}(N-p-D_1)\right]} \quad (10)$$

Some MRC transmit a tone signal (a sign of an unoccupied channel) on an unoccupied (empty) channel. In this case, the first stage detects a signal that is a sign of an unoccupied channel; the second stage detects a signal that is a sign of the beginning of broadcasting. The transition from the first to the second stage of detection is carried out in the absence of an unoccupied channel sign in the received signal. In this case, the probability of successful completion of the search for a given time in the frequency-time domain is determined by the known relations given in [3,4,5], taking into account the peculiarities of possible changes in the SHC operation mode, which is mathematically taken into account in the above expressions (1-10).

CONCLUSIONS

1. Software and hardware complexes as means of searching for signals in MRC, using sequential cyclic search and detection procedures, solve the problem of detecting signals in the frequency-time domain and are described by a well-known probabilistic mathematical model based on the theory of directed probabilistic graphs.

2. Depending on the type of control channel, SHCs can have several modes of operation. The following situations are possible in both dedicated and distributed control channels: there is no signal in the channel (the channel is empty); the channel contains a voice signal; the channel contains a digital signal, but not a control channel signal; the channel contains a control signal. This requires both changing the SHC operating modes and adjusting the description of the cyclic procedure and its mathematical model for determining thespectral components of signals in the frequency-time domain.

3.The results of calculating the probability of successful completion of the search for a signal of a distributed control channel of MRC means with three stages of detection in the time-frequency domain with one RRD and an additional assessment of the input signal level indicate an increase in search efficiency with an increase in the number of empty channels

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Математична модель одноканального пошуку сигналів з двома ступенями виявлення при радіочастотному моніторингу телекомунікаційних систем мобільного зв’язку, м. Київ.

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Програмно-апаратні комплекси багатоетапного моніторингу радіосигналів рухомого зв'язку та особливості їх режимів роботи

Анатолій Ільницький, Олег Цуканов

Анотація. На сьогодні технічні засоби радіоперехоплення, моніторингу й радіопеленгації в мережах систем мобільного радіозв’язку реалізуються у вигляді програмно-апаратних комплексів, найважливішими показниками ефективності яких вважається швидкодія, точність визначення та імовірність розпізнавання засобів рухомого радіозв’язку з їх інформаційним наповненням. Однак, питання ефективності цих комплексів і дотепер залишаються проблематичними та потребують подальшого розвитку методів і способів пошуку та виявлення сигналів засобів рухомого радіозв’язку як у частотних, так і в часових середовищах телекомунікаційних каналів та їх подальшу інформаційну обробку.

Для вирішення вказаного проблемного питання авторами розглянуто типовий варіант структурної схеми програмно-апаратного комплексу пошуку і виявлення сигналів та особливості застосування процедур багатоступеневого пошуку і виявлення сигналів при радіомоніторингу джерел радіовипромінювання систем мобільного зв’язку. Показано, що програмно-апаратні комплекси можуть мати декілька режимів роботи залежно від вигляду каналу управління.

В статті також наведені результати розрахунків значення імовірностей успішного завершення пошуку сигналу розподіленого каналу управління засобів рухомого радіозв’язку за заданий час із трьома ступенями виявлення в частотно-часовій області з одним радіоприймальним пристроїм при різній кількості пустих каналів (p = 1, 5, 9) на одному циклі пошуку. Показано, що додаткова оцінка рівня вхідного сигналу радіоприймальним пристроїм на першому ступені виявлення підвищує ефективність пошуку при збільшенні кількості пустих каналів.

Ключові слова: програмно-апаратний комплекс, радіомоніторинг, системи мобільного зв’язку, показники ефективності, швидкодія, точність визначення, пошук, виявлення.