Detection of the Frequency Hopping Spread Spectrum Signal Sources and Estimation of Their Number by Direction Finding Data

Denis S. Radchenko, Anton B. Tokarev, Alexander A. Makarov, Oleg V. Chernoyarov

***Abstract*—Analysis of the radio environment in a wide frequency band carried out by radio monitoring systems, including correlation-interferometric direction finders, involves, among other things, the detection of the frequency-hopping spread spectrum signals and the estimation of the number of sources that generate them. During the estimation, a complicating factor is that the receiving equipment operates, as a rule, in a panoramic mode, and the receiving paths of the monitoring system are sequentially retuned into adjacent frequency subbands, cyclically changing the tuning frequency within a wide frequency range. As a result, the data that one receives from the antenna pairs of the direction finding system and that are required for determining the directions to the radio sources are very fragmentary and chaotic. Whether these data can be used efficiently depends greatly on the possibility of grouping their pieces as belonging to one or several sources. Therefore, when collecting direction finding data, it is necessary to determine how many signal sources are currently operating in the analyzed frequency band. In the current study, a fast algorithm for estimating the number of transmitters exchanging information by the frequency-hopping spread spectrum signals is introduced. The algorithm does not have a very high angular resolution, but its advantages are that it requires neither a priori information on the radio emission parameters nor a detailed description of the design of the antenna system used. It is also characterized by low computational complexity. The performance of the algorithm is confirmed by the results of its full-scale tests.**

***Index Terms*—Radio monitoring, frequency-hopping spread spectrum signal, emission spectrum, correlation interferometer, estimation of the number of radio sources**

Manuscript received May 24, 2021; revised February 03, 2022. This work was financially supported by the Ministry of Science and Higher Education of the Russian Federation (research project No. FSWF-2020-0022)

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I. Introduction

A. The Peculiarities of the Studies Devoted to the Detection and Estimation of the Frequency-Hopping Spread Spectrum Signal parameters

Data transmission by frequency-hopping spread spectrum (FHSS) signals requires the use of rather complex transmitters and receivers. However, it provides some advantages, unattainable or difficult to achieve through the conventional types of radio communication. Therefore, with the progress in the field of the receiving and transmitting equipment, the interest to the FHSS signals has been steadily increasing. Still, a rather large number of studies [1]-[5] is devoted to the problem of estimating the parameters of the FHSS signals under the assumption that not only the FHSS signal in the analyzed frequency range can be observed, but also the condition holds that it is observed against Gaussian white noise, i.e. there are no other signals present in this range. These presuppositions are very rarely consistent with the practice of radio communications. In other papers, there is discussed the problem of detecting the FHSS signals in either presence or absence of a priori information concerning the parameters of the signals detected or to be detected [6]-[11]. But, in most cases, the only aim of the study is to evaluate the probability of the receiver reaction to the FHSS signals. The identification of the signal by the receiver as the FHSS one is not considered as the task.

There are various ways to monitor observable complex systems [12]-[14]. As a rule, for the analysis of the real-life radio environment, radio monitoring complexes (RMC) are used. They operate in panoramic mode and track the radio emission in a wide frequency range, where dozens and hundreds of signal sources operate in parallel with each other [15]. Radio sources (RS) using the FHSS signals run in the same frequency band together with all the other radio stations. Panoramic mode analysis presupposes a cyclical retuning of the receiving paths of the system from frequency to frequency for the sequential data collection from the adjacent frequency bands belonging to the frequency range under analysis. In this case, the elements of the FHSS signal are recorded by RMC in fragments only, with the interval of activity of FHSS signal source coinciding with the time interval of RMC data accumulation in the corresponding frequency band. This fact makes it difficult to confirm that the monitoring of FHSS signals is taking place at all, to say nothing about the estimation of the number of FHSS signal transmitters operating in parallel.

B. Detection of Frequency Hopping Spread Spectrum Signals during the Broadband Panoramic Analysis of Radio Environment

In [16]-[18], there is introduced a method of detecting FHSS signals, based on the RMC panoramic analysis mode. To identify the belonging of a set of short-term bursts of activity to the same source of the FHSS signal, in [12], it is proposed to make use of the fact that the moments of the appearance and disappearance of the elements of such a signal will be placed on the time axis according to the uniform grid, the nodes of which are spaced at a time interval corresponding to the speed of the transmitter frequency tuning. In [17], this method helps to detect FHSS transmitters operating in a range of overlapping frequencies with the same retuning speed. The idea of the detection is that, in the case of independently operating FHSS transmitters, the probability of coincidence of the moments of signals switching from the passive state to the active one and back again on the same time axis is very small, and that allows us to assume that FHSS transmitters are fairly reliably detected.

However, when the FHSS transmitters are geographically located close to each other and operate in a common range or when they are in overlapping ranges of frequencies, and all transmitters belong to the same radio network and operate within the same synchronization system, then the shift of "time grids" of the moments of signals appearing in and disappearing from the ether is caused only by the difference in the distances between the receivers and the RMC, that is Δd. If one assumes that $\Delta d < 10$ km, then the difference in the arrival time of the signals will not exceed $\Delta\tau_{\max} = 34$ μs. On the other hand, for the ability to detect signals and to estimate their number by the time of arrival to appear, such difference must be not less than 1/20 of the length of the FHSS signal element:

$$\Delta\tau \geq 1/20S,$$

where S is the frequency hopping speed of the FHSS transmitter, or otherwise:

$$S \geq 1/20\Delta\tau \approx 1500,$$

i.e., in contrast to the claims stated in [17], identification of the transmitters based on revealing the shift of the time grid nodes is not provided when the frequency hopping is carried out at speeds of less than 1500 jumps per second.

So, let the time spent on air by the synchronized FHSS transmitters is enough for the processing system to register at least a few dozens of the signal fronts. Then the proposed approach [16]-[18] makes it possible to identify this set of bursts of activity as produced by FHSS signals, but it does not allow answering the question how many different transmitters have generated these signal elements. An attempt to use the difference in the levels of received signals for their identification is also problematic. The first reason is that the conditions of multipath propagation at different frequencies can vary significantly so that the difference in the levels of the received signals is generated at the receiving point, even if these levels are the same at the transmitter. Another reason is that radio stations that emit FHSS signals often generate signal elements at different frequencies and with the notably different intensities. Thus, in Fig. 1, one can see an example of the accumulated spectrum of the signal emitted in a short time interval by a real FHSS radio station.

As it follows from the presented data, relatively low-frequency elements of the signal differ in their level by more than 20 dB from the similar elements of the high-frequency part of the radio band. Therefore, for the detection and the identification of the transmitters generating FHSS signals, one should not use these data, but the direction finding data instead.

C. The Peculiarities of the Collecting Information for Frequency Hopping Spread Spectrum Signals when Using a Correlation Interferometer

One of the types of direction finders operating in wide frequency ranges is the correlation interferometer [19], [20] that collects and co-processes phase-difference data from a large number of pairs of antenna elements (AE) constituting an antenna system. In the case of direction finding of short-range radio signals to which FHSS signals typically belong, the monopulse direction finder can demonstrate the greatest efficiency, but such direction finders are too expensive as they provide synchronous high-precision multi-channel data processing. Therefore, it is of significant interest to evaluate the possibility of indentifying the FHSS signal sources by applying much more common two-channel correlation interferometers that carry out data collection from different antenna pairs using the serial switching of antenna elements to the input of a two-channel radio receiver. A typical timing diagram demonstrating the operation of such an RMC is presented in Fig. 2. Here the notations are: τ_{out1} is the time interval during which the receiver emits signal at the fixed frequency; τ_{turn} is the time that it takes for the RMC receiver to switch to the adjacent frequency band; τ_{cycle} is the length of the monitoring cycle during which the RMC manages to collect the data for L frequency bands that constitute the frequency range under monitoring.

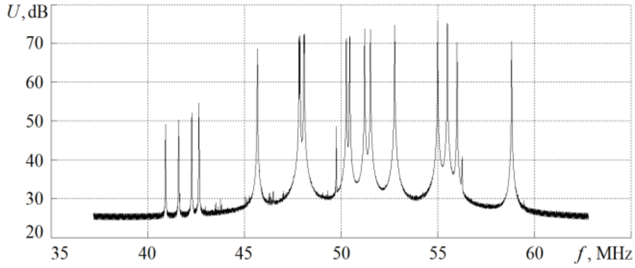

Fig. 1. The accumulated periodogram for Harris radio station.

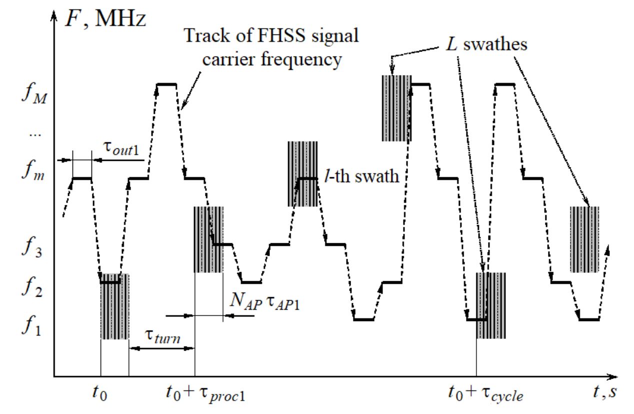

Fig. 2. Timing diagram of the FHSS signal transmitter and correlation interferometer joint operation.

When collecting data, the RMC cyclically analyzes L frequency bands, where data samples from N_{AP} antenna pairs (AP) are collected within the time interval with the duration $\tau_{getData} = N_{AP}\tau_{AP1}$, where τ_{AP1} is the length of the time series collected by the RMC from one AP, and then the receiver retunes to the adjacent frequency band ("swath").

The choice of the AP is based on the switching capabilities of the particular direction finding equipment, but rather often one of the reception channels is constantly connected to the central element of the antenna system and is referred to as the reference one, its operation does not require AE switching. The second element of the AP is included in it due to the cyclic reconnection of different elements of the antenna system to the second input channel of the receiver. Thus, one should use the broadband time series observed in the reference channel to track the fronts of the FHSS signal elements (because these time series are continuous ones within the long data collection interval $\tau_{getData}$). The data from the switched AE are compared with the time series from the reference channel and are used while collecting phase-difference data necessary for the direction finding computations.

The FHSS signals retuning from frequency to frequency can significantly complicate the process of direction finding of their sources. Fig. 2 demonstrates, where one can see that the short duration of the interval during which FHSS transmitter keeps staying at a specific frequency leads to the fact that the individual elements of the FHSS signal by the duration τ_{out1}, as a rule, are presented as just fragmentary samples and for a few pairs of AE only. In further computations, the incompleteness of the data set leads to the ambiguity of direction finding results.

When there is reliable a priori information that only a single source of the FHSS signal can operate in the analyzed frequency range, then the fragmentation of the data noted above does not play a fundamental role: using disparate phase-difference measurements as the elements of a single data set, it is possible to compute the bearing of the signal source with high accuracy and reliability [21]. However, the active use of communications using FHSS signals does not generally guarantee that one finds a single FHSS signal transmitter. When the observed radio emission elements belong to several signal sources located in different points of space, one would recommend dividing the recorded data into several subgroups according to their presumed belonging to different sources for the computation of their bearings.

It should be noted that, under the fundamental impossibility of data pre-grouping, you can try to use the computation methods that can help to solve the problem of detecting and identifying the sources and that are based on the unclassified set of direction-finding measurements. However, as a rule, such processing is accompanied by a decrease in accuracy and a significant increase in the complexity of computations. On the other hand, both with and without data pre-grouping, it is very useful to be able to estimate the number of signal sources whose bearings are to be computed.

The following part of this paper deals with the fast estimation of the number of detectable FHSS transmitters by applying the direction finding data. In this case, the purpose of processing is not to compute the bearings of the sources, but to determine whether the observed signal emitting elements belong to a single source or the registered elements are generated by two or more transmitters spaced apart from each other. At the same time, the term "fast estimation" means that to decide on the number of FHSS transmitters one should use a minimum amount of computing and time resources.

II. Method for Estimating the Number of Frequency-Hopping Spread Spectrum Transmitters

A. Basics of the Frequency Hopping Spread Spectrum Signal Sources Detection Procedure That Does Not Require Information Concerning the Geometry of the Antenna System

For further analysis, it is necessary to study the phase relations that accompany the signal reception by the antenna system elements [22].

Let the vector $\vec{r}_1 = (x_1, y_1, z_1)^{\mathrm{T}}$ is a single vector coinciding with the direction of the first (and, possibly, the only) source, while $\vec{R}_j = (X_j, Y_j, Z_j)^{\mathrm{T}}$ is the radius vector that defines the spatial position of the j-th antenna array element (Fig. 3).

Then the difference of the wave path from the j-th AE to the center of the antenna array can be calculated as [19]

$$\Delta_j = \vec{r}_1^{\,\mathrm{T}} \vec{R}_j$$

and the phase correction for the reception of the electromagnetic wave by the j-th element of the antenna system is

$$\Delta\varphi = 2\pi \left(X_j x_1 + Y_j y_1 + Z_j z_1 \right) / \lambda . \quad (1)$$

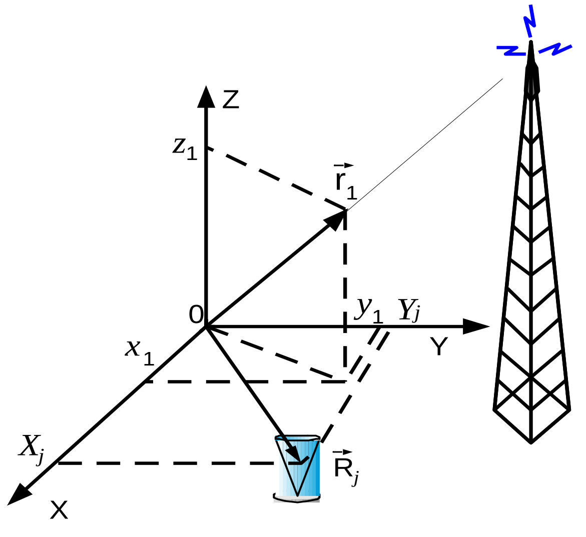

Fig. 3. The relative positions of the FHSS signal source and the antenna system elements.

In (1), λ is the wavelength of the oscillation being born. For any antenna pair, the phase shift between the oscillations received by the two elements of the antenna system of the direction finder is determined as

$$\Delta\Phi_{j1,j2}(f,\vec{r}_1) = 2\pi f\left[\left(X_{j1} - X_{j2}\right)x_1 + \right. \\ \left. + \left(Y_{j1} - Y_{j2}\right)y_1 + \left(Z_{j1} - Z_{j2}\right)z_1\right]/c\,, \tag{2}$$

where c is the speed of electromagnetic wave propagation and f is the frequency of the oscillation.

If during the data collection interval both the antenna system of the direction finder and the source of the FHSS signal are stationary, then the proportionality coefficient included in (2) and determined by the mutual arrangement of the AP and the radio source, is a certain constant for each AP. And if the duration of the FHSS signal monitoring is large enough to allow the collection of phase-difference data at different frequencies (even if these data are fragmentary), then, at adjacent frequency positions for each AP, the change of the phase difference is a linear function of the frequency. Moreover, when using antenna systems, the geometric dimensions of which are limited by meters, and the spectrum width does not exceed 10 MHz, the maximum possible change in the phase shift within the signal frequency band satisfies the relation

$$\Delta\Phi_{j1,j2}(f_{\max},\vec{r}_1) - \Delta\Phi_{j1,j2}(f_{\min},\vec{r}_1) \le \\ \le 2\pi\left(f_{\max} - f_{\min}\right)\left|\vec{R}_j\right|/c << 2\pi\,. \tag{3}$$

The frequencies $f_{\min} \ldots f_{\max}$ used to transmit information are usually quite high so that the central frequency of the spectrum

$$f_c = 0.5\left(f_{\max} + f_{\min}\right) \tag{4}$$

is equal to tens or hundreds of megahertz. In such conditions, for the AP with orientation in space not too different from $\vec{r}_1$, the phase shift $\Delta\Phi_{j1,j2}(f_c,\vec{r}_i)$ may be noticeably greater than 2π. As a result, for two transmitters spaced apart from each other at a sufficiently large angular distance, one or several AE pairs are nearly always available among the AP of the correlation interferometer such that the differences between $\Delta\Phi_{j1,j2}(f_c,\vec{r}_1)$ and $\Delta\Phi_{j1,j2}(f_c,\vec{r}_2)$ are significant.

Thus, if all the FHSS signal elements that can be monitored are generated by a single transmitter, then for each AP the unique phase shift value $\Delta\Phi_{j1,j2}$ occurs, and it remains practically unchanged when the transmitter retunes by the frequency. If the correlation interferometer registers the elements of the FHSS emission generated by the different sources that are markedly spaced apart from each other, then there exists at least one AP producing, for the set of FHSS signal elements, the two groups of observations differing by the phase shift $\Delta\Phi_{j1,j2}$. Thus, the presence of two (or several) FHSS transmitters simultaneously can be detected by the multimodal distribution of the phase shift $\Delta\Phi_{j1,j2}$.

The fact that the measured values $\Delta\Phi_{j1,j2}$ are subject to significant fluctuations due to the presence of noise complicates the identification of the FHSS sources. During computing bearings, such fluctuations may lead to errors in determining the azimuth of the FHSS source; reducing the impact of these fluctuations upon the results of the direction finding computations can be reached by averaging a large number of measurements from the entire set of the antenna system AP. However, when testing hypotheses about the possible number of jointly operating FHSS transmitters, such averaging is impractical obviously. It is potentially possible to increase the reliability of the FHSS sources identification using the joint processing of data coming from several antenna pairs, but the number of pairs showing noticeable phase shifts is always small, and the search for a subset of AP suitable for the FHSS sources identification is a very time-consuming procedure. Thus, identification of the one AP demonstrating the most substantial phase shift values serves as a good basis for designing the computationally efficient fast detection and identification algorithm.

B. Choice of the Decision Determining Statistics and Detection Threshold

To calculate phase shifts corresponding to different frequencies, it is advantageous to use the samples of mutual 2-channel spectrum. As the first step of its computation, the discrete spectrum is calculated for the time series from each of the l-th AEs as follows

$$\dot{c}_l(n) = \sum_{k=0}^{N-1} x_l(k)\exp\left(-\frac{j2\pi nk}{N}\right),$$

where $x_l(k)$ is the sequence of time domain samples obtained from l-th AE at the observation interval, n is the reference number of the spectral sample corresponding to the frequency

$$f_n = f_0 + nF_s / N . \quad (5)$$

In (5), f_0 is the tuning frequency of the receiver, F_s is the sampling frequency, N is the dimension of discrete Fourier transform.

Then, for each of the AP, the mutual spectrum is determined in the following way

$$\dot{c}_{j1,j2} = \dot{c}_{j1}(n)\,\dot{c}^*_{j2}(n)$$

and then the phase shifts are calculated using the mutual spectrum samples:

$$\Delta\Phi_{j1,j2}(f_n, \vec{r}) = \arg\{\dot{c}_{j1,j2}(n)\}. \quad (6)$$

To identify the features of the phase shifts grouping for each of the AP, a histogram of the distribution of $\Delta\Phi_{j1,j2}$ values is constructed. When choosing the parameters for the histograms to be formed, the following factors should be taken into account:

a) even when there are received the strictly harmonic signals against the background of the noise, the phase Θ of sum oscillation is fluctuating, and, in case when signal-to-noise ratio (SNR) is less than 20 dB, the range of the phase values is about $\pm 10^\circ$, while under $\text{SNR} = 30\,\text{dB}$ this range is reduced, but remains equal to $\pm 3^\circ$, at least (Fig. 4);

b) when receiving the elements of the FHSS signal, the phase fluctuations generated by noise are summed up with the changes induced by the signal modulation features;

c) the phase shifts $\Delta\Phi_{j1,j2}$ are formed as the difference between the two independent random variables Θ_1 and Θ_2, and that approximately doubles the variance;

d) finally, as it follows from (3) the effect of changing the phase shift along the frequency axis, while the resulting spectrum is not too wide, is nor clearly expressed, but still influences on the set of the estimates (6).

These factors indicate that building the histograms using

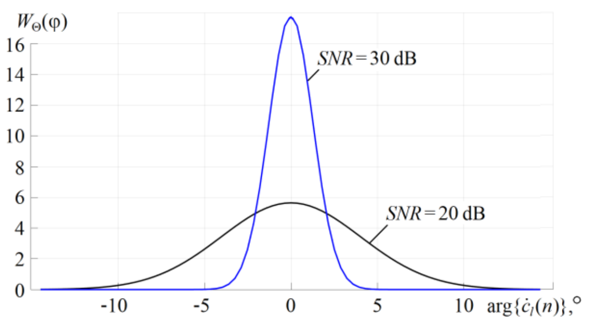

Fig. 4. Phase distributions of harmonic signal and noise mix.

the narrow bars is justified only when one is dealing with the powerful signals. For practical use, the bar $10\ldots15^\circ$ wide can be recommended. Moreover, into these histograms, one should insert only such phase shifts that have been obtained for the short-term emission elements. With such a selection, the built histograms depend only on the elements of FHSS signals and the emission of the packet data networks, if any are available in the analyzed frequency range, as well as on noise fluctuations that can be mistakenly perceived as the short-term radiation elements.

In order to improve the accuracy and reliability of the FHSS transmitter identification problem solution, it is advisable to reject the signals of packet networks. If the frequency at which RMC registers packets of radio signals is constant, it is a reliable sign that a set of phase shifts, located in one, two or three adjacent histogram bars, is generated not by FHSS signals, but by the source of the radio network with packet data transmission. As for the noise fluctuations, the phase shifts generated by them are distributed uniformly in the angular direction, and therefore they have no significant effect on the peaks and dips of the histograms. Let us use a histogram with a bar that is 15° wide. If one of the 24 bars gets more than $12\ldots16\,\%$ of the values, it almost certainly indicates the existence of the real radio source causing the corresponding phase shift [23].

Thus, when estimating the number of FHSS transmitters operating in the controlled frequency range, it is necessary to

– compute the phase shifts (6) for all the short-term radiation elements registered for each of the AP;

– create the histograms demonstrating the distribution of these values;

– remove the elements generated by the signals of the packet radio networks from the histogram;

– determine, for each histogram, the number of local histogram maxima exceeding the $12\ldots16\,\%$ threshold value.

The number of FHSS transmitters is determined by the maximum number of detected local maxima among all the histograms created for different AP belonging to a certain antenna system.

C. Peculiarities of the Procedure for the Detection of the Wideband Frequency Hopping Spread Spectrum Signals

If the frequencies used to transmit the FHSS signal belong to the frequency interval which is wider than 10 MHz, it is dangerous to neglect the change in phase shift. At the same time, the rule (2) determines the linear pattern of the interrelationship between the values of $\Delta\Phi_{j1,j2}$. Therefore, while processing FHSS signals occupying wide frequency bands, the algorithm presented above should be modified.

Under the traditional approach, it is assumed that the i-th bar of the histogram includes phase shifts that differ from the average value $\Delta\Phi_i$ by no more than half the width of the bar, i.e. the following inequality holds

$$\left|\Delta\Phi_{j1,j2}\left(f,\vec{r}_1\right)-\Delta\Phi_i\right|<180^\circ/I_{\text{hist}}\ , \qquad (7)$$

where I_{hist} is the number of bars in the histogram. Then, to the values acceptable for hitting into the *i*-th bar one should also assign the phase shifts fitting the "oblique" bars, i.e., satisfying the condition

$$\left|\Delta\Phi_{j1,j2}\left(f,\vec{r}_1\right)-\Delta\tilde{\Phi}_{ij}\right|<180^\circ/I_{\text{hist}}\ . \qquad (8)$$

Here $\Delta\tilde{\Phi}_{ij}=\Delta\Phi_i\pm\pi\left(f-f_c\right)\left(\left|\vec{R}_{j1}\right|+\left|\vec{R}_{j2}\right|\right)/2c$, f is the frequency of the current element of the FHSS signal; f_c is the central frequency of its spectrum (4); and c is the electromagnetic wave propagation velocity speed.

While building the histograms, for each *i*-th bar and among the values corresponding to (7) and (8), one should choose the greatest ones, tracking and controlling the cases of repeated (double) use of the same values of $\Delta\Phi_{j1,j2}$ in different bars. Attempts to distribute the same phase shifts $\Delta\Phi_{j1,j2}$ between different histogram bars (possible with a modified approach for frequencies close to $f_{\min}$ or $f_{\max}$) should be "penalized" by assigning a half-weight to such shifts, while non-overlapping distribution types should be promoted by assigning a "full weight" to the number of the elements falling into the bar.

D. Factors Influencing the Reliability of the Frequency Hopping Spread Spectrum Signal Sources Detection and Recommendations for Histogram Smoothing

Let two FHSS transmitters with comparable emission levels and the frequency retuning with the rates of tens or hundreds of jumps per second operate simultaneously on air. Then the probabilities of the FHSS emission element registration by both sources are close to each other, and hence the average number of histogram elements belonging to different transmitters and registered by each AP is approximately the same. If the transmitters are geographically spaced so that the phase shifts (6) they produce differ significantly at the analyzed AP, then the two separate bursts of comparable height are observed in the histogram. Reduction of the angular distance between the transmitters leads to the decreasing differences in the phase shifts and the bursts in the histograms will converge. For successful identification of the transmitters, between the histogram maxima, they produce, the minimum should fit, represented by at least one histogram bar.

One should take into consideration that the reliability of the algorithm is influenced by both the choice of the histogram bar width and the procedure of histogram creation. The use of narrow bars can provide the improvement of angular resolution, but it is dangerous because of the possibility of an erroneous identification. If the distribution of the phase shifts $\Delta\Phi_{j1,j2}$ is quite shallow and occupies a width of 3 or more bars of the histogram, then the probability of the appearance of a false dip in the center of such a shallow burst increases sharply due to random fluctuations in the measurements. When wide histogram bars are used, it results in low resolution.

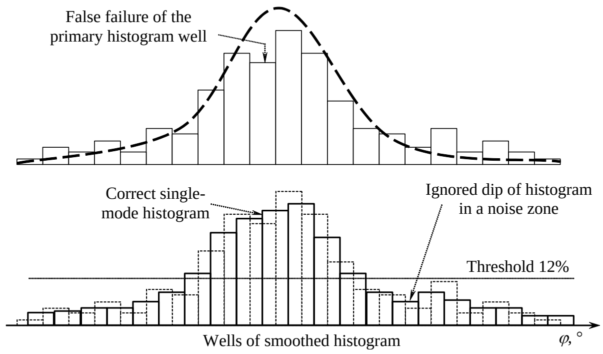

Fig. 5. Smoothing technique for secondary histograms.

A reasonable alternative is data smoothing [24], which assumes that the values in adjacent bars of the primary histogram are averaged as it is shown in Fig. 5. It allows eliminating false dips of the primary histogram arising from the unsuccessful division of the angular axis into the bars. Data smoothing decreases the angular resolution of the algorithm, however, it can also significantly decrease the probability of false detection of sources and therefore can be recommended for use.

In the practical implementation of the algorithm proposed above for estimating the number of FHSS transmitters operating on the air, a separate, rather difficult task is to optimize the duration of the phase difference information accumulation stage.

When building histograms based on no more than 10-20 cycles of the frequency range scanning, it is almost impossible to obtain an informative histogram of phase shifts, because the elements of this histogram are phase shifts for intercepted radio pulses of short duration. However, for wide frequency bands, the probability that the radio monitoring system will analyze the next *l*-th of the *L* bands exactly when the FHSS transmitter emits a radio signal in the *l*-th band is very small. Accordingly, the time period required to collect the data needed for histogram building should be at least tens, and, preferably, hundreds of scanning cycles.

On the other hand, with a significant increase in the length of the data collection procedure, another danger becomes more and more important. The transmitters that are the purpose of the study are not on the air all the time, and after completing the information transmission, they stop operating and may be further inactive for a long time. Thus, the intervals of a joint presence of two (or more) FHSS transmitters on the air will be substituted by the time intervals when only one of them is active. Naturally, in the histogram, the relative proportion of phase shifts corresponding to the operating transmitter will grow, and for the transmitter that has stopped operating, it will decrease. As a result, if the accumulation of data in the histogram is carried out without a time limit, then the peaks exceeding the detection threshold can be generated only for such FHSS transmitters that repeatedly on the air.

So, for the FHSS transmitters that use short-term transmission sessions (i.e., their duration does not exceed several tens of information collection cycles performed by the radio monitoring system), but with equally short pauses between the broadcasts, the length of the data collection interval does not matter. If, on the other hand, the broadcasts of a FHSS transmitter are considerably long alternating with equally considerable pauses between them, then the attempts to estimate FHSS emissions by the histograms accumulated over a significantly longer time interval will be accompanied by a noticeable decrease in the probability of their detection.

A detailed analysis of the requirements for the duration of data accumulation that would ensure a high probability of the presence of bursts exceeding the threshold in the histograms of phase shifts, is a difficult probabilistic problem. Therefore, in the present paper, only an approximate analysis of the corresponding problem is focused on. It means the following restriction: for each of the allowed transmitters only $N_{\min}$ phase shifts are to be registered on average during the time of data collection. In practice, the required value of $N_{\min}$ depends on the selected signal detection threshold. When attempting to detect weak radio emissions along with the actual FHSS signals, the radio monitoring system captures many random noise bursts. Thus, $N_{\min} >> 10$ is the most reasonable choice. If, however, a high detection threshold is used, and the rejection of the signals that fall into the analyzed band, but do not belong to the FHSS class, is performed quite successfully, then the choice of $N_{\min} \approx 20$ can be considered acceptable.

Since within each individual cycle of the radio monitoring system operation, for a specific AP in a specific frequency band, data collection is performed only over an interval with a duration τ_{AP1}, the conditional probability of a successful registration of a separate frequency position emitted on the air can be estimated as [19]

$$p_1 = \frac{\tau_{AP1}}{\tau_{cycle}} = \frac{\tau_{AP1}}{LN_{AP}\tau_{AP1}(1+\beta)} = \frac{1}{LN_{AP}(1+\beta)},$$

where $\beta = \tau_{turn}/\tau_{getData}$ is the coefficient determining the time required for the retuning of the radio monitoring system to the adjacent frequency band.

It is presupposed that a FHSS transmitter emitting a signal with a frequency hopping rate of S hops per second continue to operate on the air without interruption throughout the entire accumulation interval τ_{all}. Then the total number of frequency positions that it can build during this interval is $A = \tau_{all} S$. As for the expected average number of phase shifts that can by entered into the transmitter's spectrogram during the time interval τ_{all} it is calculated as $N_{\Delta\Phi} \approx \tau_{all} S / LN_{AP}(1+\beta)$.

From the requirement $N_{\Delta\Phi} \geq N_{\min}$ it follows that the recommended data accumulation time needed for the histogram building is $\tau_{all} \geq N_{\min} LN_{AP}(1+\beta)/S$. For example, if the analyzed range includes $L = 25$ adjacent frequency bands, 9-element AP ($N_{AP} = 9$)is used, and a frequency hopping interval is characterized by the coefficient $\beta = 1$ [19]. Then, for detecting the FHSS transmitters with a frequency hopping rate of $S = 300$ hops per second, the data accumulation duration needed for histogram building should meet the requirement $\tau_{all} \geq 20 \cdot 25 \cdot 9 \cdot (1+1)/300 = 30$ seconds.

III. Results and Discussion

The fast algorithm for estimating the number of transmitters using FHSS signals described above has been implemented in the hardware of maintenance-free radio monitoring direction finder ARTICUL-SN [25] shown in Fig. 6. Radio stations «Harris» that can be seen in Fig. 7 have been used as the detectable objects.

In preparation for the full-scale tests, the direction finding complex has been placed at the test sit, while the radio stations have been tuned to emit FHSS signals with matching frequency hopping rates. During the experiment, the radio stations were moved around the test sit to ensure they can be observed from different directions with different angular spacing.

The detection algorithm testing described in Section 2.B leads to the conclusion that

1) the approach introduced in [16]-[18] makes it possible to identify the broadcasting of the FHSS transmitters and to determine the set of frequencies corresponding to the elements of the FHSS signals;

2) under a transmitter angular spacing that does not exceed 30°, the presented fast algorithm does not provide FHSS sources identification;

3) under SNR exceeding 20 dB, the sustainable identification of FHSS sources is provided with the transmitter angular spacing greater than 40°; under SNR below 20 dB, for the correct determination of the number of

Fig. 6. Maintenance-free radio monitoring direction finder ARTICUL-SN.

Fig. 7. Radio station «Harris».

FHSS transmitters, the angular spacing should be greater than 50°.

4) As a result, the proposed algorithm makes it possible to distinguish cases when two callers exchange information (indicating the angular directions for each of the transmitters), from the case when only one RS is broadcast to transmit information, and sometimes (with a significant angular separation of the frequency hopping transmitters relative to the point of a direction finding complex placement) can also recognize cases of joint presence of 3-4 transmitters on the air. To recognize a larger number of simultaneously operating transmitters, the analyzed algorithm is not suitable. The first reason for this is the insufficient angular resolution of the algorithm. Another reason lies in the fact that the process of "capturing" by the direction finding complex of "data portions" generated on the air by different FHSS transmitters is never perfectly balanced, and the number of intercepted data packets for different transmitters operating on the analyzed frequency will always noticeably differ. This means that for data from the most actively operating transmitter(s), the probability of obtaining a well with a height exceeding 12 ... 16% of the values in the histogram of phase differences is relatively easy. But, however, for the transmitters whose emissions, due to a random coincidence, have been rarely recorded, the chances of forming a histogram well with a height exceeding such a threshold are very small. At the same time, it is not recommended to lower the threshold level, because this will most likely lead to a sharp increase in the rate of false positives of the algorithm as a whole.

IV. Conclusion

The paper discusses the problem of estimating the number of transmitters using frequency hopping spread spectrum signals in the panoramic analysis of the radio environment carried out by a correlation interferometer. The fast chaotic frequency retuning by the operating signal transmitter bands passes through asynchronous overlapping with the cyclic change of the receiving band of the direction finding equipment and thus generates a set of disparate measurement fragments making their optimal processing much more problematic. The technicalities and complexity of the processing procedure significantly depend on whether the analyzed frequency band has a single FHSS radio source or several FHSS transmitters operate simultaneously. As a consequence, an algorithm is required that would allow establishing the presence of one or more FHSS signal transmitters without significant computational costs.

The computationally efficient algorithm introduced for estimating the number of transmitters using FHSS signals does not have a very high angular resolution. Under a high signal-to-noise ratio, it provides the detection of two transmitters spaced apart from each other by about 40°. Under lower signal-to-noise ratios, the on air broadcast presence of more than one FHSS signal source can be revealed only when the angular spacing of the transmitters is not less than 50°. For these and some other statistical reasons, it can be useful for the detection of the presence of 1or 2, and sometimes up to 4 sources in the air, but no more. The low angular resolution of the algorithm is compensated by the simplicity, low computational cost, suitability for use in panoramic view mode of radio monitoring equipment, as well as by minimal need for a priori information about the characteristics of the FHSS transmitters. The algorithm is insensitive to the characteristics of the antenna system of the correlation interferometer and can be used even in the absence of information about the geometry of the receiving antenna of the direction finder.

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