UDK: 621.396.662.5-501.2 (047)-20
COSATI: 17-02

An algorithm for parameter estimation of frequency hopping emitters and their separation and grouping in unique radio networks

Ivan P. Pokrajac, BSc (Eng)1)
Miljko Erić, PhD (Eng) 1)
Miroslav L. Dukić, PhD (Eng) 2)

An algorithm for parameter estimation of frequency hopping emitters and their separation and grouping in unique radio networks based on estimated parameters is proposed in this paper. Estimation of parameters of frequency hopping signals is based on the spatio-time- frequency signal analysis.

Key words: **radio surveillance systems, radio network, frequency hopping, antenna array, signal analysis, signal processing, algorithm.**

Introduction

MODERN radio surveillance systems have to intercept signals with unknown parameters in very complex multiple incident signal scenario in environments of high noise and interference. Furthermore, surveillance systems are often faced with the low probability-of-intercept (LPI) signals such as spread spectrum signals.

Frequency hopping-FH signals are a class of spread spectrum signals. Interception of frequency hopping signals is a very complex and challenging technical problem. In typical tactical situation more classical as well as frequency hopping emitters with unknown signal parameters are active at the same time as a frequency sub-band. These unknown parameters have to be estimated from the radio signal received in the given frequency band and time observation interval.

Modern radio surveillance systems have to provide detection of FH signals, estimation of direction-of-arrival (DOA), separation of FH signals from narrowband signals, separation and grouping of FH transmitters in unique radio networks.

An algorithm for the estimation of FH signal parameters such as: hop duration, frequency shift and distance between two adjacent frequency channels in case when many of FH signals are more superposed on antenna array, is presented in this paper. The algorithm is based on the spatial-time-frequency signal analysis. An algorithm for separation and grouping of FH transmitters in unique radio networks is proposed and presented as well.

Spatial model of radio signal superposition on antenna array

Summary received radio signal $u(t)$ on antenna array in a selected spectral bandwidth $\Delta\omega_{BW}$ and observed time interval ΔT is the result of superposition of many radio signals $\{u_k(t)\}; k=1,..,K$ which arrive from different radio transmitters and noise $n(t)$. It can be expressed in analytical form in the following way:

$$u(t)=\sum_{k=1}^{K} u_k(t)+n(t)=\sum_{k=1}^{K} s_k(t)\exp(j\omega_{Ck}t)+n(t), \quad (1)$$

The processes of detection, parameter estimation of the superposed signals and information channel separation are based on the spatio-time-frequency signals analysis of summary signal $u(t)$ which is available in the assigned spectral bandwidth $\Delta\omega_{BW}$ and time observed interval ΔT. It is assumed that there is no information about the number, statistical and spectral characteristics of the superposed signals.

Generalized spatial model of the superposed signals can be expressed in the time domain as, [1]:

$$\boldsymbol{x}(n)=\sum_{h=-H/2}^{H/2}\left[\boldsymbol{A}(\omega_c,\omega_h)\boldsymbol{F}(\Omega_h)+\boldsymbol{N}(\Omega_h)\right]\exp(j2\pi\Omega_h n), \quad (2)$$

where $\mathbf{x}(n)=\left[x_1(n)\quad x_2(n)\quad ...\quad x_L(n)\right]^T$ is the vector with the spatial-temporal samples of the IQ demodulated signal in the selected spectral bandwidth on an antenna array of arbitrary geometry. Ω_h is the normalized frequency and it has the value in the interval $\Omega_h\in[-0.5,0.5]$. The spatial model of the superposed signals on the antenna array in the frequency domain can be expressed as:

$$\mathbf{X}(\Omega_h)=\mathbf{A}(\omega_C,\omega_h)\mathbf{F}(\Omega_h)+\mathbf{N}(\Omega_h), \quad (3)$$

where

---

1) Military Technical Institute, (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

2) Faculty of Electrical Engineering, Kralja Aleksandra 73, 11000 Belgrade, SERBIA

$$\mathbf{X}(\Omega_h)=\left[X_1(\Omega_h)\quad X_2(\Omega_h)\quad \dots\quad X_L(\Omega_h)\right]^T$$

is a vector with spectral samples of the signals on the antenna array;

$$\mathbf{F}(\Omega_h)=\left[F_1(\Omega_h)\quad F_2(\Omega_h)\quad \dots\quad F_L(\Omega_h)\right]^T$$

is a vector with spectral samples of shifted complex envelopes of the superposed signals;

$$\mathbf{N}(\Omega_h)=\left[N_1(\Omega_h)\quad N_2(\Omega_h)\quad \dots\quad N_L(\Omega_h)\right]^T$$

is a vector with spectral samples of noise on the antenna array.

$F_k(\Omega_h)$ is a shifted spectrum of the complex envelope of the k-th superposed signal and it can be expressed in the following way:

$$\begin{aligned} F_k(\Omega_h) &= \sum_{n=1}^{N} s_k(n\Delta t)\exp\left[j(\omega_{Ck}-\omega_C)n\Delta t\right]\exp(j2\pi\omega_h n\Delta t) = \\ &\sum_{n=1}^{N} s_k(n\Delta t)\exp\left[j2\pi\Omega_{Ck}n\right]\exp(j2\pi\Omega_h n) = \\ &\sum_{n=1}^{N} f_k(n\Delta t)\exp(j2\pi\Omega_h n). \end{aligned} \tag{4}$$

The vector $\mathbf{F}(\Omega_h)$ contains information about the spectral bandwidths and central frequency of the superposed signals.

Spectral components of $\mathbf{F}_k(\Omega_h)$ are symmetrically distributed around the normalized central frequencies $\left\{\Omega_{Ck}=\dfrac{\omega_{Ck}-\omega_C}{\Delta\omega_{BW}}=\dfrac{f_{Ck}-f_C}{\Delta f_{BW}}\right\}, k=1,..,K$. Based on the known central frequency ω_C of the selected spectral bandwidth and estimated normalized central frequencies $\{\Omega_{Ck}\}, k=1,..,K$ the central frequencies of superposed radio signals $\{\omega_{Ck}\}, k=1,..,K$ can be calculated.

The matrix $\mathbf{A}(\omega_C,\omega_h)$ has the *LxK* dimension. Columns of this matrix are the so called *steering vectors* of the superposed signals, which can be expressed in the normalized form as:

$$\left[\exp\left(j2\pi\left(\frac{\omega_C+\omega_h}{\omega_A}\right)\boldsymbol{v}_k^T\frac{\boldsymbol{r}_1}{\lambda_A}\right)\dots\exp\left(j2\pi\left(\frac{\omega_C+\omega_h}{\omega_A}\right)\boldsymbol{v}_k^T\frac{\boldsymbol{r}_L}{\lambda_A}\right)\right]^T \tag{5}$$

where $\mathbf{r}_\ell \in R^3$ is the location vector of the ℓ-th antenna in real 3-D space, $\mathbf{v}_k \in R^3$ is a unit vector which represents the direction-of-arrival of the k-th signal on the antenna array and it can be expressed in the spherical coordinate system as a function of the Direction Of Arrival - DOA (azimuth θ_k and elevation φ_k) as:

$$\mathbf{v}_k=\left[\sin(\theta_k)\cos(\varphi_k)\quad \cos(\theta_k)\cos(\varphi_k)\quad \sin(\varphi_k)\right]. \tag{6}$$

In order to formulate the spatial model of superposition of signals, it is necessary to formulate a mathematical model of complex envelope of the FH signal at the reference point in space. Distribution of energy spectrum signal with FH in the temporal-frequency domain in the selected spectral bandwidth $\Delta\omega_{BW}$ and observed time interval ΔT and basis parameters which are needed for the mathematical modeling of the complex envelope of FH signal is presented in Fig.1.

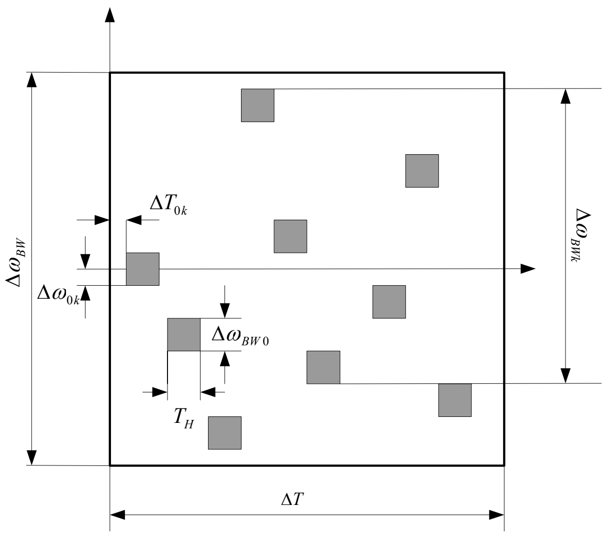


Figure 1. Distribution of energy of the FH signal in time-frequency domain.

Parameter $\Delta\omega_{BWk}$ denotes the spreading bandwidth of the *k*-th signal in the observed time interval ΔT, while $\Delta\omega_{BW0}$ is the spectral bandwidth of the elementary narrowband frequency channel. Parameter $\Delta\omega_{0k}$ denotes frequency-shift, and ΔT_{0k} is the time-shift of the *k*-th hop in relation to the origin of the coordinate system. These parameters are defined because transmitters can belong to different hoppers or radio networks which are not time synchronized. Those radio networks can use different distances between two adjacent hop frequencies as well. Parameter $M_h=\Delta\omega_{BW}/\Delta\omega_{BW0}$ presents a possible number of hop channels in the selected spectral bandwidth $\Delta\omega_{BW}$. Parameter $N_h=\Delta T/T_H$ is the total number of hops in the time observation interval ΔT.

Based on previously defined parameters, the complex envelope $s_k(t)$ of the k-th FH signal can be expressed in discrete frequency domain [3,4] as:

$$\begin{aligned} s_k(n) &= \sum_{v=1}^{N_h}\exp\left[j2\left(\frac{\gamma_{kv}\Delta\omega_{BW0}-\Delta\omega_{0k}}{\Delta\omega_{BW}}\right)n\right] \\ &\sum_{h=-H/2}^{H/2} S_{kv}(\Omega_h)\exp\left[-j2\pi\Omega_h\left((v-1)n_h-n_k\right)\right] \\ &\exp(j2\pi\Omega_h n). \end{aligned} \tag{7}$$

where n_h is the number of time samples in one hop, n_k is the number of temporal samples for which the beginning of the first hop is time shifted in relation to the origin of the coordinate system. The hop ordering number is marked by $v=1,..,N_h$, $\gamma_{kv}\in(-M_h/2, M_h/2)$ is the code sequence of the hopper, and $S_{kv}(\Omega_h)$ is a complex envelope of the v-th hop.

Band segmentation and spreading bandwidth estimation of the FH signal

The algorithm for spectrum segmentation which is presented in [1, 5] is based on the Direction of Arrival - DOA estimation in the frequency domain using MUltiple Signal Classification algorithm - MUSIC and joins all the spectral components with the same estimated DOA in the same information channel. It is assumed that the radio transmitters do not change DOA on the antenna array in the time observation interval ΔT . The algorithm for spectrum segmentation is based on the estimation of the parameters of the generalized spatial model of superposition radio signals in a selected frequency sub-band, [1].

Some results of numerical simulation which illustrate the proposed algorithm for band segmentation and spreading bandwidth estimations of FH signals are presented in this paper. In the first example a circular antenna array with five elements is used. Characteristic (Niquist) frequency of antenna array is $f_A = 80$ MHz. Selected frequency sub-band is $\Delta f_{BW} = 6.4$ MHz with central frequency $f_C = 70$ MHz. FH signals from two radio networks are superposed on the antenna array. There are three active frequency hopping emitters in each radio network. Azimuths of arrivals for FH signals from the first radio networks are [45°, 20°, 0°], and [-60°, -30°, -115°] for FH signal from the second radio network. Elevations of arrival for all frequency hopping emitters are equal to 0°. The distances between the two adjacent frequency channels are 25 kHz and 12.5 kHz for FH signals from the first and the second radio network, respectively. There are $M_{h1} = 256$ and $M_{h2} = 512$ possible number oh hoping frequencies for FH signals from the first and the second radio network, respectively. Normalized spreading bandwidth is (-77/256, 50/256) for FH signals from the first radio network and it is (-155/512, 100/512) for FH signals from the second radio network. The number of time samples per hop is $n_{h1} = 25600$ $\left(n_{h2} = 23273\right)$, which is equivalent to hop duration of $T_{H1} = 4\,\text{ms}$ $\left(T_{H2} = 3.6364\,\text{ms}\right)$ or to the hop rate of 250 hop/s and 270 hop/s for FH signals from the first and second radio networks, respectively. Frequency-shift is $\Delta f_{01} = 5$ kHz in the first radio networks and $\Delta f_{02} = 4.5$ kHz in the second radio network. Signal to noise ratios are [15, 18, 15 dB] for the first and [20, 20, 15 dB] for the second radio network, respectively. BFSK modulation with bit rate of 12.8 kb/s and 6.4 kb/s is applied on each hop.

The results of band segmentation for the first simulated example in the observed time interval of $\Delta T = 0.297$ s are presented in Fig.2. The results provided by the proposed algorithm for band segmentation for the previous example and for two values of the observation time interval $\Delta T = 0.594\,s$ and $\Delta T = 0.891\,s$ are presented in Figures 3 and 4.

It can be seen from Fig.2 that hops with the same DOA are jointed to the same information channel and further, the number of active FH emitters in the selected frequency sub-band and time observation interval and their directions of arrival (DOA) on the antenna array can be estimated. For spreading bandwidth estimation of FH signals longer observed time interval ΔT is needed. For FH signals with big hop rate smaller observed time interval is needed than for signals with small hop rate, provided that that both FH signals use the same frequency sub-band.

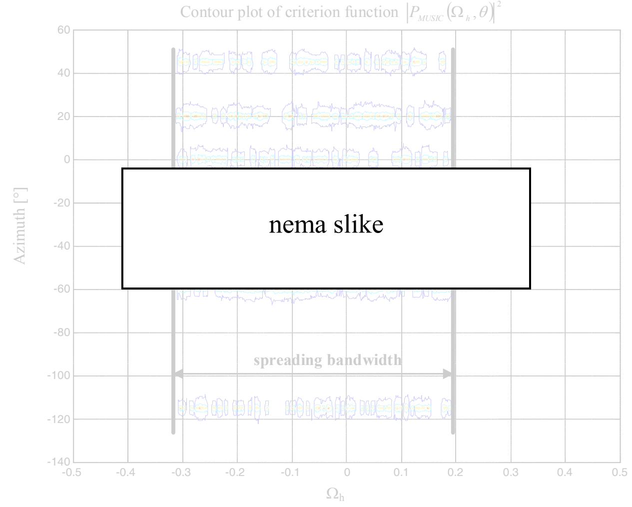


Figure 2. Contour plot of $|P_{MUSIC}(\Omega_h,\theta)|^2$ for the time observed interval $\Delta T = 0.297\ s$.

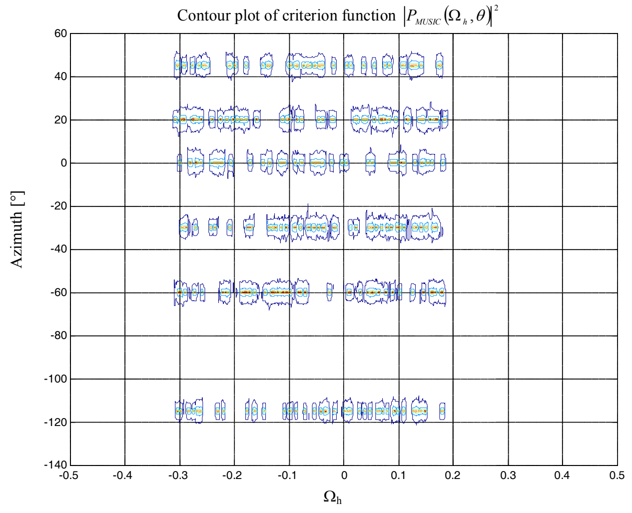


Figure 3. Contour plot of $|P_{MUSIC}(\Omega_h,\theta)|^2$ for the observed time interval $\Delta T = 0.594\ s$.

Based on the results which are presented in Figures 2 - 4 it can be concluded that the estimation of the spreading bandwidth of FH signals becomes better and better as the duration of the time observation interval is increased.

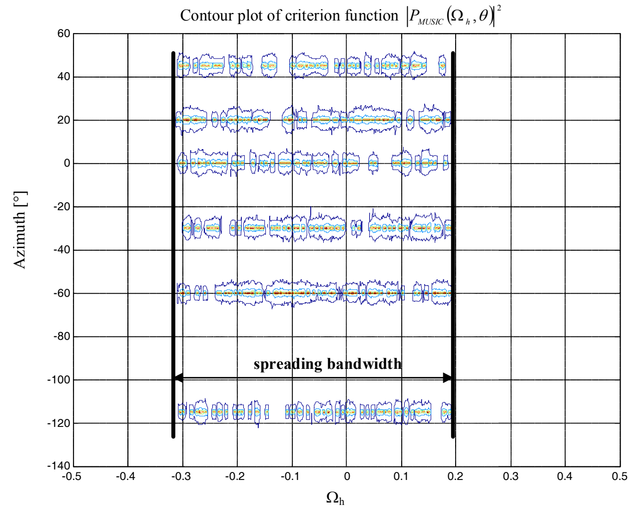


Figure 4. Contour plot of $|P_{MUSIC}(\Omega_h,\theta)|^2$ for the observed time interval $\Delta T = 0.891\ s$.

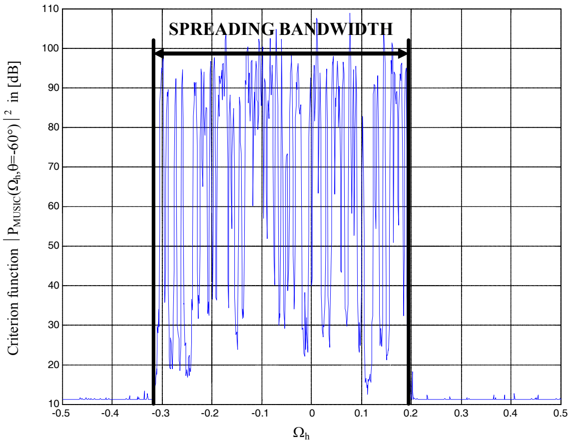


Figure 5. Plot of $\left|P_{MUSIC}\left(\Omega_h,\theta=-60^\circ\right)\right|^2$ for the time observation interval $\Delta T = 0.891\,s$.

It can be concluded from Fig.4 that all FH signals in the simulated scenario have approximately the same spreading bandwidth.

The results of border estimation of the normalized spreading bandwidth of the superposed FH signals are given in Table 1. Error in spreading bandwidth estimation is not bigger than 60 kHz.

The results of band segmentation for the second simulated example are presented in Fig.6. In this case, circular antenna array with six elements is used. Characteristic frequency of the antenna array is $f_A = 80$ MHz. The frequency sub-band is $\Delta f_{BW} = 6.4$ MHz and it is cantered on the frequency of $f_C = 70$ MHz.

Table 1. Estimated normalized border of spreading bandwidth for the first simulated example.

Num.of net.	Border of spreading bandwidth	Assigned border	Estimated border	Error [kHz]
I net	lower normalized frequency	-0.3008	-0.31	58.88
	upper normalized frequency.	0.1953	0.2	30.08
I I net	lower normalized frequency	-0.3027	-0.31	46.72
	upper normalized frequency.	0.1953	0.2	30.08

Eleven signals are superposed on the antenna array. Nine of them are FH signals, and the others are signals on fixed frequencies. FH signals are separated in three radio networks. In each of them there are three active frequency hopping users. Azimuths of arrivals are [95°, 76°, 84°, -22°, -33°, -44°, 0°, 30° and 17°] for signals from the first, the second and the third radio networks, respectively. Azimuths of arrivals of the signal of the fixed frequency emitters are [50°, -10°], respectively. Elevations of arrivals are 0° for all signals. The distances between two adjacent frequency hoping channels are 25 kHz, 25 kHz and 6.25 kHz for the first, the second and the third radio networks, respectively. It is clear that there is total $M_{h1,2} = 256$ possible hoping frequencies for signals from the first and the second radio networks, whereas there are $M_{h3} = 1024$ possible hoping frequencies for signals from the third radio network. The borders of the normalized spreading bandwidth are (-64/256, 64/256), (-8/256, 120/256), (-256/1024, 256/1024) for the first, the second and the third radio networks, respectively. The number of time samples per hop are $n_{h1} = 25600$, $n_{h2} = 25098$ and $n_{h2} = 24615$, which is equivalent to the hop duration of $T_{H1}=4\ ms$, $T_{H2}=3.9215\ ms$, $T_{H2}=3.8461\ ms$. or to the hop rate of 250hop/s, 255 hop/s and 260 hop/s for signals from the first, the second and the third radio networks, respectively. Frequency-shifts are $\Delta f_{01} = 10$ kHz, $\Delta f_{02} = 7.5$ kHz and $\Delta f_{03} = 1$ kHz. BFSK modulation with the bit rate of 16 kb/s and 3.2 kb/s is applied in the first and the second radio networks. In the third radio network 4FSK modulation with the bit rate of 16 kb/s is applied.

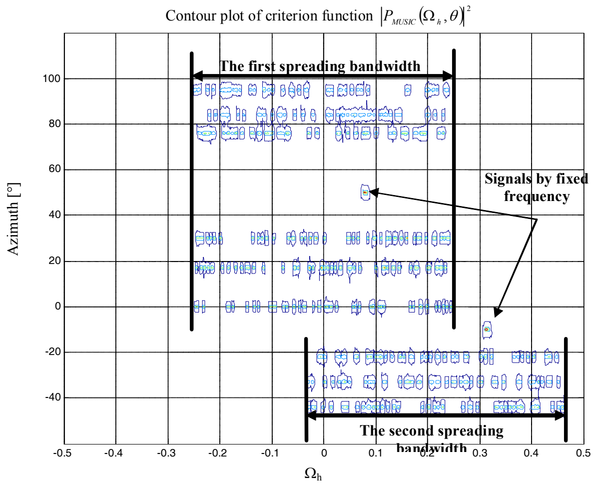


Figure 6. Contour plot of $\left|P_{MUSIC}\left(\Omega_h,\theta\right)\right|^2$ for the time observation interval $\Delta T = 0.891\,s$.

It can be concluded from the results presented in Fig.6 provided by the proposed band segmentation algorithm, that six active FH emitters share approximately the same spreading bandwidth. The other FH emitters use different spreading bandwidths. The results of border estimation of the normalized spreading bandwidth of FH signals are presented in Table 2. It can also be concluded from the presented results that normalized error of spreading bandwidth estimation is acceptably small. In the simulated scenario, maximal value of the normalized error of spreading bandwidth estimation is less than 35/64000.

Parameter estimation of FH signals

Identification of information channels, parameter estimation and separation of the superposed signals are basic problems in the process of automatization of monitoring and analysis of radio-frequency spectrum. Modern radio surveillance systems have to detect the FH signals, estimate the parameter of FH signals, estimate locations of the detected FH transmitters, separate and group the FH transmitters in unique radio networks.

Usually, these processes require estimation of additional parameters of the detected FH signals such as: hop duration (hop rate), frequency-shift, distance between two hopping frequencies, hop initial time, etc.

An algorithm for hop duration estimation of the selected FH transmitter in a situation when many FH signals are superposed on the antenna arrays which belong to different radio networks is presented in the paper [5] (see Fig.7).

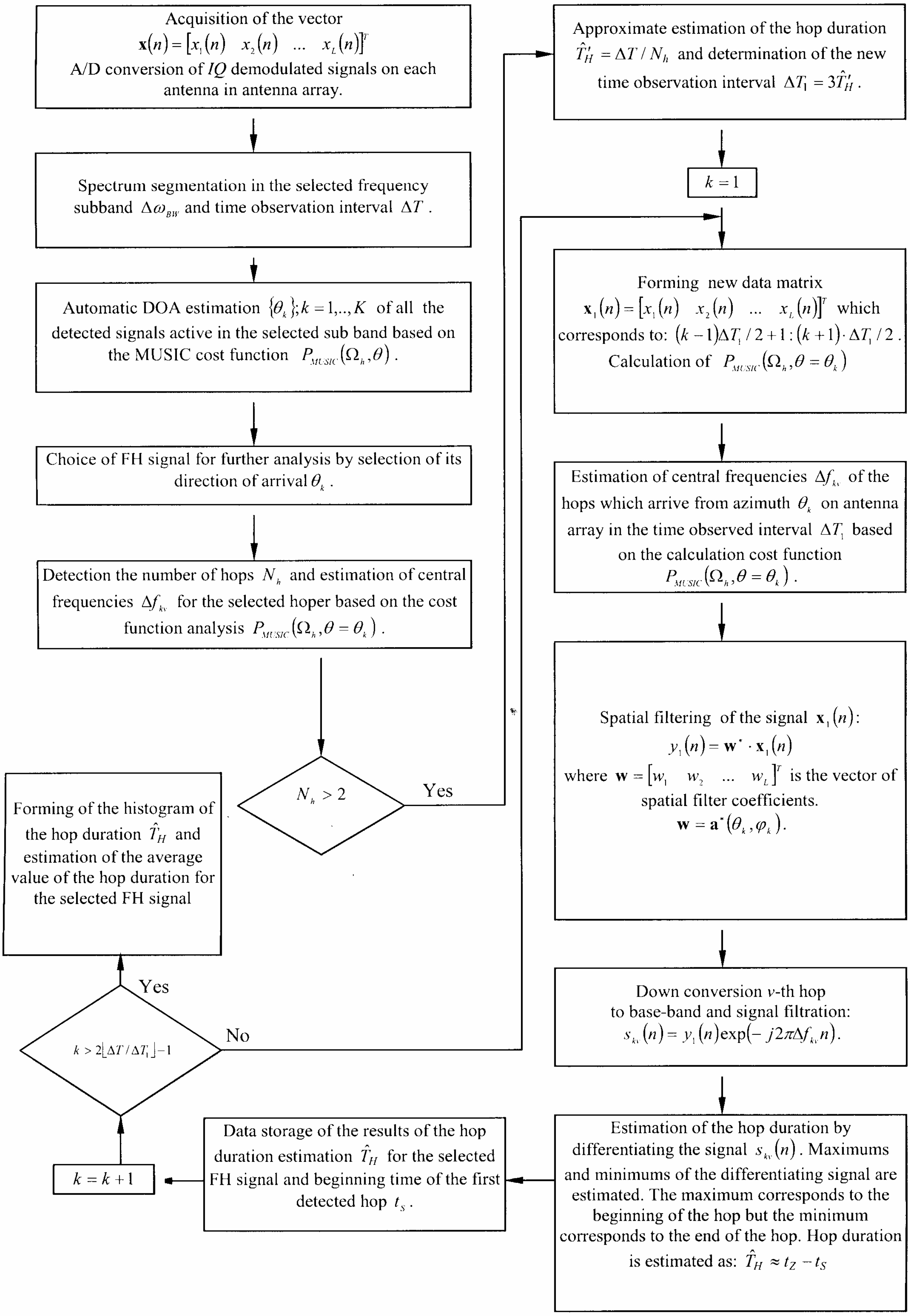


Figure 7. Block scheme of the algorithm for hop duration estimation of the FH signal

Table 2. Estimated normalized border of spreading bandwidth for the second simulated example

Num. of net.	Border of spreading bandwidth	Assigned border	Estimated border	Error [kHz]
I net	lower normalized frequency	-0.25	-0.25	0
	upper normalized frequency	0.25	0.248	12.8
II net	lower normalized frequency	-0.0313	-0.0325	7.68
	upper normalized frequency	0.4688	0.4635	33.92
III net	lower normalized frequency	-0.25	-0.25	0
	upper normalized frequency	0.25	0.248	12.8

It was presupposed that hop duration estimation and band segmentation procedures are based on the use of *LxN* complex spatio-time samples of signal arriving on the antenna array which is available in the observed time interval ΔT and selected frequency band $\Delta\omega_{BW}$. These samples are provided by IQ demodulation/down conversion performed at each antenna and time discretisation. Also, it was supposed that the time observation interval ΔT is much larger than hop duration T_H $\left(\Delta T >> T_H\right)$.

Automatic DOA estimation of the superposed signals $\{\theta_k\}; k=1,...,K$ is performed based on the results provided by the algorithm for band segmentation that is calculating criterion function $P_{MUSIC}\left(\Omega_h,\theta\right)$ of the MUSIC algorithm. After that step, it is necessary to select FH signals which will be further analyzed. This selection is based on the estimated DOA of the selected hoppers. Estimation of the number of detected hops is based on the values of the $P_{MUSIC}\left(\Omega_h,\theta=\theta_k\right)$ for the selected azimuth and further, the estimation of hop duration $\hat{T}_H = \Delta T / N_h$ can be simply performed.

In order to estimate hop duration correctly, algorithm for band segmentation has to be applied again in the same selected frequency band, but in a new time observed interval $\Delta T_1 = 3\hat{T}_H$. In this case, criterion function $P_{MUSIC}\left(\Omega_h,\theta=\theta_k\right)$ is determined only for the selected azimuth. Estimation of the number of hops and their central frequencies Δf_{kv} can be simply performed using previous results.

After the estimation of the central frequencies of the hops, the superposed signal is spatially filtered in the selected direction on the estimated central frequencies. After that the signal is down converted to base-band according to the result of the estimation of the central frequencies of each hop. A complex envelope of each hop is estimated in this way. Hop duration is determined by estimating the time interval between maximum and minimum of the differentiated complex envelope of each hop. These maximums and minimums correspond to the beginning and ending of each hop. Correct estimation of hop duration is performed after analysis of all the estimated values of hop durations in the observed time interval ΔT with the selected azimuth of arrival.

The results of estimation of the hop duration of FH signals for the first and second simulated signal scenarios are presented in Table 3 and 4.

Table 3. The results of estimations of hop duration of FH signals for the first simulated example

Azimuth in [°]	Correct value of T_H [ms]	Estimated value of T_H [ms]	Error in [μs] and [%]
45°	4	3.9996	0.4 (0.01)
20°	4	3.9996	0.4 (0.01)
0°	4	3.9992	0.8 (0.02)
-60°	3.6364	3.6384	2 (0.055)
-115°	3.6364	3.6376	1.2 (0.032)
-30°	3.6364	3.6373	0.9 (0.025)

It can be concluded that the proposed algorithm provides correct estimation of the hop duration (the relative error of hop duration estimation in the simulated scenario is smaller than 1%).

Supposed hop durations in the simulated signal scenario correspond the hop duration of the modern frequency hopping equipment. According to the available references and relevant experience, the modern VHF/UHF FH radios do not use hop rates bigger than 350 hop/s.

Table 4. The results of estimations of hop duration of FH signals for the second simulated example

Azimuth in [°]	Correct value of T_H [ms]	Estimated value of T_H [ms]	Error in [μs] and [%]
95°	4	4.0025	2.50 (0.0625)
76°	4	4.0020	2.03 (0.0507)
84°	4	4.0023	2.34 (0.0585)
-22°	3.9215	3.9234	1.87 (0.0477)
-33°	3.9215	3.9248	3.28 (0.0836)
-44°	3.9215	3.9208	0.78 (0.0199)
0°	3.8461	3.8451	0.93 (0.0242)
30°	3.8461	3.8476	1.56 (0.0405)
17°	3.8461	3.8489	2.81 (0.0730)

The distance between two adjacent frequency channels is determined based on the estimation of the central frequency of the frequency channels which are estimated in the time observation interval ΔT. After estimating the central frequencies of the frequency channels, the estimated central frequencies are sorted in increasing order and difference between adjacent frequencies is calculated.

The distance between two adjacent frequency channels correspond to the minimal values of the difference.

Typical distance between two adjacent frequency channels in all most modern VHF/UHF FH radios is 6.25/12.5/25 kHz. In order to estimate the distance between two adjacent frequency channels correctly, the time observation interval has to be as long as possible.

Frequency-shift estimation of the channels is based on the estimation of the histogram of the instantaneous frequency of each hop complex envelope. Complex envelope of the hop is provided after estimation of the central frequency of the actual hop, spatial filtering in the selected DOA and down conversion of each hop to base-band.

Separation and grouping of FH transmitters in unique radio networks

The results of estimation of frequency-shift and distance between the two adjacent frequency channels for the first and second simulated examples are presented in Table 5. The results of grouping of FH transmitters for the first signal scenario based on the estimated parameters of FH the signals which are given in Tables 3 and 5 are presented in Fig.8.

It can be seen from Fig.8 that it is possible to group FH transmitters in unique radio networks using the estimated parameters such as: hop duration, frequency-shift and distance between two adjacent frequencies.

Table 5. Estimated parameters of FH signals.

I example			II example		
Azimuth [°]	Frequency-shift [Hz]	Distance between two adjacent frequencies [kHz]	Azimuth [°]	Frequency-shift [Hz]	Distance between two adjacent frequencies [kHz]
45°	5009,2	25	95°	9993,7	25
20°	5002,7	25	76°	10071,0	25
0°	5002,8	25	84°	9998,9	25
-60°	4507,7	12.5	-22°	7490,3	25
-115°	4469,0	12.5	-33°	7497,3	25
-30°	4505,8	12.5	-44°	7502,4	25
---	---	---	0°	997,9	6.25
---	---	---	30°	1006,5	6.25
---	---	---	17°	1003,7	6.25

The results of FH separation for the second simulated example are presented on the Fig.9.

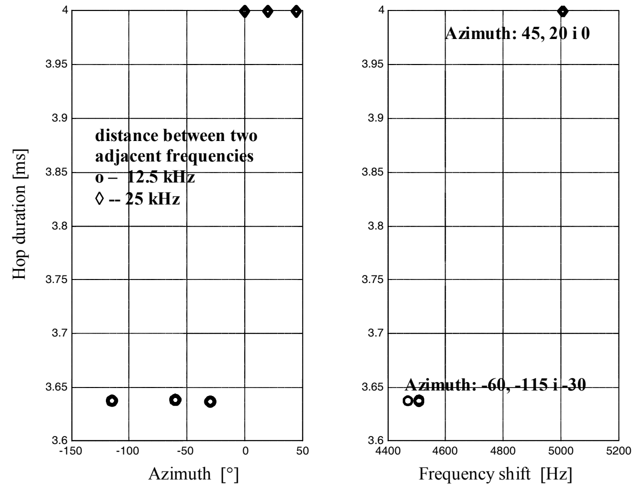
From the results presented in Fig.9 it can be concluded that it is possible to separate and group FH transmitters in unique radio networks based on the estimated parameters of the FH signals even when FH transmitters use the same spreading bandwidth. In the presented example FH signals from the first and second radio networks use frequency sub-band, but other parameters are different. Based on these parameters it is possible to separate and group all active FH transmitters in unique hopping radio networks.

The results of parameter estimation of FH signals and possibility of their separation and grouping in unique radio networks when FH signals have the same parameters as hop rate and frequency-shift, but use different spreading bandwidth are presented in the third simulated example.

In this simulated example FH signals are received using circular antenna array with eight antenna elements. Characteristic frequency of the antenna array is $f_A = 80$ MHz. The frequency sub-band of $\Delta f_{BW} = 6.4$ MHz is used for hoping, centred on the frequency of $f_C = 70$ MHz. Twelve FH signals are superposed on the antenna array. FH signals are separated in four radio networks.

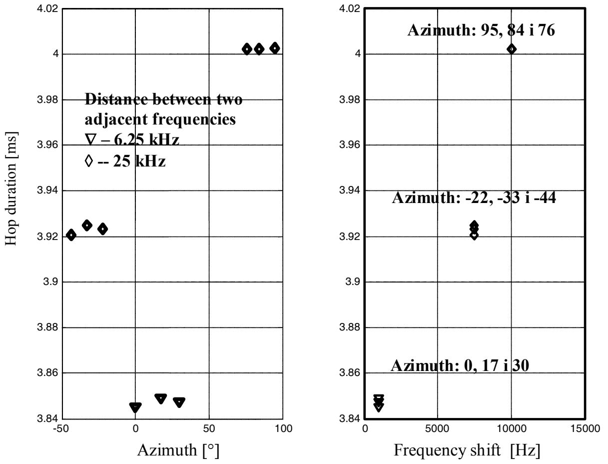
The first two radio networks have three active hoppers, the third has four hoppers and the fourth has two hoppers. Azimuths of arrivals are [18°, 22°, 28°], [12°, 0°, 4°], [88°, 80°, 83°, 86°] and [-125°, -120°] for signals from the first, second, third and fourth radio networks, respectively. Elevation is 0° for all signals. The distances between two adjacent frequency channels are 25 kHz, 25 kHz, 12.5 kHz and 12.5 kHz for the first, second, third and fourth radio networks, respectively.

It is clear that there are $M_{h1,2} = 256$ possible frequency hoping channels in the first and second radio networks and $M_{h3,4} = 512$ possible frequency hoping channel in the third and fourth networks in the selected frequency sub-band.



a) **b)**

Figure 8. Grouping FH transmitters based on the estimated parameters of FH signals: a) diagram *azimuth-hop* duration, b) diagram *frequency shift-hop duration.*



a) **b)**

Figure 9. Grouping of FH transmitters based on the estimated parameters FH signals for the second simulated example: a) diagram azimuth-hop duration,, b) diagram frequency shift-hop duration.

The borders of the normalized spreading bandwidth are (-28/256, 100/256), (-118/256, 10/256), (-156/512, 100/512), (-56/512, 200/512) for the first, second, third and fourth radio networks, respectively. The number of time samples per hop are $n_{h1,2} = 23704$, $n_{h3,4} = 25600$, which is equivalent to the hop duration of $T_{H1,2}=3.7037$ *ms*, $T_{H3,4}=4$*ms*, or to the hop rate of 270 hop/s and 300 hop/s for signals from the first, second, third and fourth radio networks, respectively. Frequency-shifts are $\Delta f_{01} = 6.25$ kHz, $\Delta f_{02} = 6$ kHz and $\Delta f_{03,4} = 5$ kHz. 4FSK signals with bit rate of 8 kbit/s are transmitted in the first and second radio networks, respectively. BFSK signals with bit rate of 6.4 kbit/s are transmitted in the third and fourth radio network

The results of hop duration estimation for the third simulated example are presented in Table 6. Error of hop duration estimation is not bigger than1%. The same value of error occurs in the first two simulated examples.

Table 6. The results of hop duration estimation of FH signals for the third simulated example.

Azimuth [°]	Correct value of T_H [ms]	Estimated value of T_H [ms]	Error [μs] and [%]
18°	3.7037	3.7056	1.9 (0.05)
22°	3.7037	3.7031	0.6 (0.016)
28°	3.7037	3.7044	0.7 (0.019)
-12°	3.7037	3.7023	1.4 (0.037)
0°	3.7037	3.7081	4.4 (0.12)
4°	3.7037	3.7069	3.2 (0.086)
80°	4.0000	3.9996	0.4 (0.01)
88°	4.0000	4.0003	0.3 (0.008)
83°	4.0000	4.0009	0.9 (0.024)
86°	4.0000	4.0006	0.6 (0.016)
-125°	4.0000	4.0001	0.1 (0.003)
-120°	4.0000	4.0000	0 (0.00)

Based on the results which are presented in Fig. 10 it can be seen that the number of all active hoppers in the selected frequency sub-band and time observation interval and its directions of arrivals can be clearly identified. Also, it can be noticed that three spreading bandwidths exist.

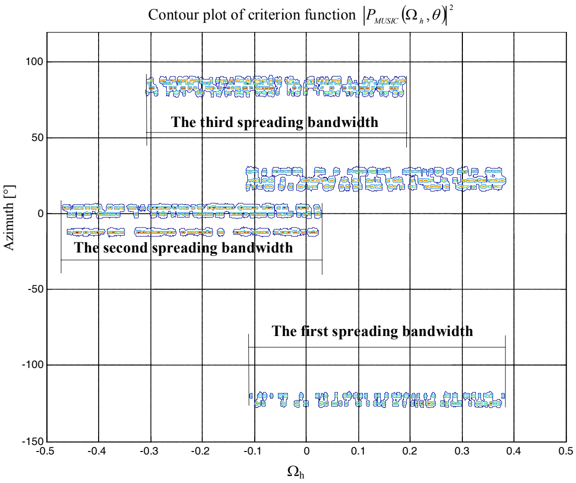


Figure 10. Contour plot of $\left|P_{MUSIC}(\Omega_h,\theta)\right|^2$ for the observed time interval $\Delta T = 0.891$ s.

Table 7. Estimated parameters of FH transmitters.

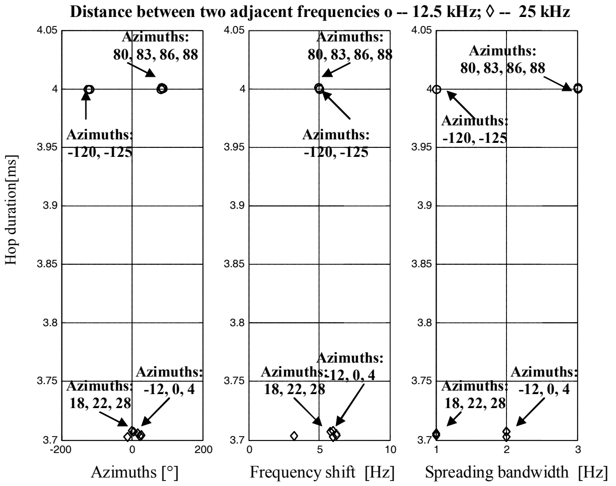
III example			
Azimuth [°]	Frequency-shift [Hz]	Distance between two adjacent frequencies [kHz]	Spreading bandwidth
18°	6.254	25	1
22°	3.214	25	1
28°	6.24	25	1
-12°	5.98	25	2
0°	6.00	25	2
4°	5.78	25	2
80°	5.01	12.5	3
88°	5.00	12.5	3
83°	4.95	12.5	3
86°	4.99	12.5	3
-125°	5.00	12.5	1
-120°	5.01	12.5	1

The results of estimation of other parameters of FH signals are presented in Table 7. It can be seen that just for the hoper with azimuth of 22° in the first radio network frequency-shift is estimated with significant error.

Grouping of the FH transmitter is performed using previously estimated parameters given in Tables 6 and 7. The results of grouping of FH transmitters in unique radio networks are presented in Fig. 11. From the results presented in Fig. 11a and 11b it can be seen that it is not possible to separate FH transmitters from the first and the second radio networks.

In order to separate and group these FH transmitters in unique radio networks, other information such as DOA, locations of FH transmitters, possibility of communication between FH transmitters has to be used. Another way is using the information about spreading bandwidth of FH signals. Based on the additional information, it is possible to separate and group FH transmitters in unique radio networks. It can also be concluded that frequency-shift is estimated with significant error for an FH signal with azimuth of 22° and it belongs to the first radio network.

In case when FH signals from the first and second radio networks use the same spreading bandwidth, without other parameters it is not possible to effectively separate and group FH transmitters in unique radio networks.



a) b) c)

Figure 11. Grouping FH transmitters based on the estimated parameters of the FH signals for the third simulated example: a) diagram *azimuth-hop duration*, b) diagram *frequency shift-hop duration*, c) diagram *frequency shift- hop duration*.

Conclusion

An algorithm for parameter estimation of frequency hopping emitters and their separation and grouping in unique radio networks is presented in this paper. It can be applied in multiple incident signal scenarios when many FH signals from different radio networks as well as classical narrowband signals are superposed on the antenna array.

It can be concluded from the presented results that the algorithm for hop duration estimation FH signals gives correct results with error smaller than 1% of the accurate hop duration.

Also, the algorithm for estimating the frequency-shifts and distance between two adjacent frequency channels provides correct estimation of these parameters.

It can also be concluded that it is possible to group and separate active FH transmitters in unique radio networks based on the estimated parameters of the FH signals using spatio-time-frequency signal analysis.

References

[1] ERIĆ M.: *Spatio-frequenty analysis of the radio frequency spectrum*, PhD dissertation, Faculty of Technical Science, Novi Sad 1999.

[2] ERIĆ M., OBRADOVIĆ M.: *The method for spatio-frequency signal analysis*, Invited paper presented on VII symposium TELFOR, Beograd, November 1999.

[3] ERIĆ M., DUKIĆ M., OBRADOVIĆ M.: *Frequency hopping signal separation by spatio-frequency analysis based on the MUSIC method*, IEEE 6th International Symposium on Spread Spectrum Techniques and Applications (ISSSTA 2000), NJ, USA, September 2000.

[4] ERIĆ M.: *Separating FH signals based on spatio-frequency analysis using the MUSIC method*, XLIII ETRAN conference, Zlatibor, 20-22 September 1999.

[5] POKRAJAC I., ERIĆ M., DUKIĆ M.: *Hop rate estimation of FH transmitters based on spatio-temporal-frequency signal analysi*, IV symposium INDEL, Banja Luka, 14-16 November 2002.

Received: 12.12.2003.

Procena parametara signala sa frekvencijskim skakanjem i razdvajanje predajnika sa frekvencijskim skakanjem i njihovo grupisanje u jedinstvene radio mreže

U ovom radu prikazani je algoritam za procenu parametara signala sa frekvencijskim skakanjem i mogućnosti razdvajanja predajnika sa frekvencijskim skakanjem i njihovo grupisanje u jedinstvene radio mreže na osnovu procenjenih parametara. Procena parametara signala sa frekvencijskim skakanjem zasniva se na prostorno-frekvencijsko-vremenskoj analizi signala.

Ključne reči: **radio-izviđački sistem, radio mreža, frekventno skakanje, antenski niz, analiza signala, obrada signala, algoritam.**

Оценка параметров сигналов со частотными прыжками и разделение передатчика со частотными прыжками и их группирование в объединённые радиосети

В настоящей работе приведён алгорифм для оценки параметров сигналов со частотными прыжками и возможности разделения передатчика со частотными прыжками и их группирование в объединённые радиосети на основании оценнёных параметров. Оценка параметров сигналов со частотными прыжками обосновывается на просторно-частотно-временном анализе сигналов.

Ключевые слова: радиоразведывательная система, радиосеть, частотные прыжки, антенный массив, анализ сигналов, обработка сигналов, алгорифм.

Un algorithme pour les paramètres d’estimation des signaux avec saut de fréquence et leur groupement en réseaux de radio uniques

Dans ce papier on a présenté un algorithme pour l’estimation des paramè - tres chez les signaux avec saut de fréquence et les possibilités de séparer les émetteurs avec saut de fréquence et leur groupement en réseaux de radio à partir des paramétres estimés. L’estimation des paramètres chez les signaux avec saut de fréquence est basée sur l’analyse temporelle, spatiale et celle de fréquence des signaux.

Mots clés: **système de radio détection, réseau da radio, saut de fréquence, série d’antennes, analyse des signaux, traitement des signaux, algorithme.**