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Throughput Capacity of RF Sensor for Unmanned Aerial Vehicle

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Usage of small unmanned aerial vehicles (UAVs) for spectrum sensing, especially in urban areas, has numerous advantages over the use of ground-based stations for radio frequency (RF) emitters detection and location. In order to develop spectrum sensing equipment for UAVs, it is necessary to establish a number of requirements for it. One of the main requirements is the necessary throughput capacity. The purpose of the article is to improve the methodological apparatus to establish requirements for UAVs spectrum sensing equipment. To describe the density of RF emitters distribution, it is proposed to use a nonhomogeneous Poisson spatial process in combination with parametric or nonparametric distribution functions. The density function of this distribution reflects the average number of RF emitters that are within energy accessibility and can be detected. Using a quantile of a given Poisson distribution level, in which the density function is used as a parameter, allows to estimate maximum number of RF emitters. The signal flow from each RF emitter is described using a nonstationary Poisson process. The moments of time of broadcast and the duration of signal emission are exponentially distributed. Estimates of the average intensity of RF emitters during analyzed time interval of a given frequency band for a single-channel multi-antenna system have been obtained. The methodology for estimating the required throughput capacity of RF sensor and recommendations for using the proposed methodological apparatus in conditions of a priori uncertainty regarding the density of RF emitters distribution and signal flow intensity are presented. Using the values of the maximum number of RF emitters within the energy availability range for the entire spectrum sensing area, the average intensity of RF emitters, and the analysis time of the instantaneous frequency band, it was obtained an estimate of required throughput capacity of RF sensor.

Keywords: radio frequency emitter; RF sensor; throughput capacity; Poisson process; spatial density; signal flow; unmanned aerial vehicle

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Introduction

The rapid development of unmanned aerial systems allows them to be used for a wide range of tasks, including spectrum sensing [1, 2]. The use of small unmanned aerial vehicles (UAVs) to detect and assess the location of radio frequency (RF) emitters has a number of significant advantages over stationary radio monitoring devices [3–5]. Complete coverage of RF emitters can be ensured by establishing requirements for the necessary throughput capacity of RF sensor, which determines the number of receiving frequency channels that must be created for real-time analysis of RF signals within the energy accessibility range. To do this, it is necessary to develop mathematical models of the spatial distribution density of RF emitters and signals flow from them, as well as a methodology for estimating the number of RF emitters that need to be detected and evaluating their spatial parameters.

Related works

A significant number of scientific publications are devoted to model spectrum sensing processes using UAVs, in particular, to the development of mathematical models of RF emitters density distribution on a plane. In [6], it is shown that under general conditions, the position of RF emitters can be described using a Poisson distribution. For modeling nonhomogeneous radio networks of base stations, [7] proposes using a Poisson cluster process. In [8, 9], a point Poisson process is used to model interference in heterogeneous radio networks. To model a radio network with clustering properties in [10] was proposed to use Gaussian-Poisson process, which has a simpler structure than the general Poisson point process. In [11], it is proposed to model interference fields using the Poisson process. In [12], a point Poisson process is used to model the spatial distribution of RF emitters, with the restriction that two emitters cannot be located closer than a certain distance to each other. Also some papers devoted to problems of sensors throughput capacity

[13–15]. In [16] it is shown that it is difficult to achieve a large data collection rate because sensors usually have limited energy and communication resources. In [17] throughput of underwater wireless sensor nodes is investigated.

An unresolved issue remains the assessment of the required throughput capacity of RF sensor for UAVs using mathematical modeling of spatial distribution density of arbitrary types of RF emitters and signals flow from them over relatively large areas of terrain.

Problem statement

The purpose of the article is to improve the methodological apparatus to establish requirements for UAV based RF sensors by taking into account mathematical models of the spatial-temporal distribution of RF emitters signals.

1 Spatial distribution of FR emitters modelling

To estimate the required throughput capacity of UAV based RF sensor, let us consider parametric and non-parametric mathematical models that can be used to represent the density of the spatial distribution of RF emitters on a plane in a given area (Fig. 1). The density of RF emitters placement (shown as a heat map) is directly related to population density. Since the latter is nonhomogeneous, the density of RF emitters will also be nonhomogeneous, especially in large urban areas.

For a parametric model, the density of RF emitters distribution on a plane can be represented analytically as a two-dimensional function $\lambda(x, y)$, which takes only positive values over the entire domain.

Kernel estimates are often used for nonparametric representation of distribution density [18]. The parameters for implementing this method are kernel type (window) and smoothing bandwidth h. The Gaussian kernel is most often used [19] because it provides the best smoothing. The choice of h is a compromise because it determines the degree of smoothing. Too small value of h will result in the display of unimportant sample details. Choosing a large value of h will result in the loss of some information due to excessive smoothing. The kernel estimate of the RF emitters distribution density can be written as follows:

$$\lambda(x, y) = \frac{1}{Lh} \sum_{j=1}^{L} \mathrm{K}\left(\frac{x - x_j}{h}, \frac{y - y_j}{h}\right), \qquad (1)$$

where

$K()$ – kernel function;

L – kernels number used to describe the density distribution of RF emitters in spectrum sensing area.

Let us assume that for the given parameters of RF sensor, at a certain typical signal-to-noise ratio, the detection range of signals is R. Then the area in which RF emitters will be detected will approximately be $S = \pi R^2$.

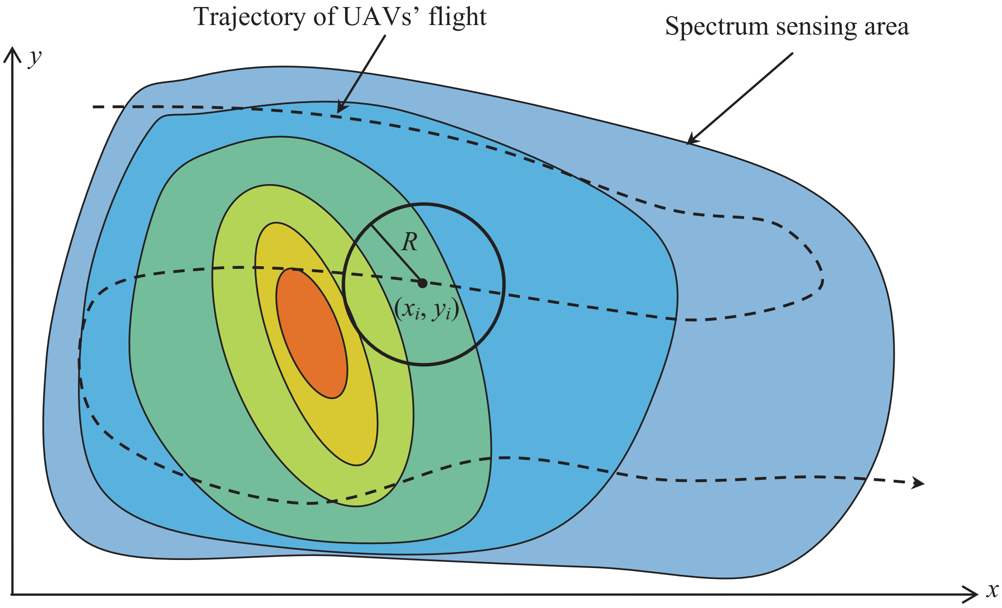


Fig. 1. Placement of detection region within the spectrum sensing area

The density function describing the average number of RF emitters N_{ei} falling within the i-th circle with area S will be calculated using the following equation:

$$E\left(N_{ei}\left(S\right)\right)=\Lambda_{Ri}=\int\limits_{S}\lambda\left(x-x_i,y-y_i\right)dxdy, \qquad (2)$$

where
$x_i=x_0+i\Delta x$, $y_i=y_0+i\Delta y$ – coordinates of i-th spectrum sensing region;
x_0, y_0 – coordinates of the point of UAV entry into spectrum sensing region;
Δx, Δy – distances that UAV move during sensing time;
$(\Delta x)^2+(\Delta y)^2=(\Delta R)^2$ – UAV displacement to calculate the new density function value.

To simplify calculations, it is advisable to switch to the polar coordinate system with some angle φ. We will select the value of ΔR based on the following considerations: when the circle is moved, the density of RF emitters distribution should not change significantly. When the UAV is moved by a distance of ΔR, the previous and subsequent detection areas will intersect by the following amount in relation to the detection area:

$$\delta S=\frac{\varphi-\sin\left(\varphi\right)}{\pi}, \qquad (3)$$

where the value of angle φ is calculated in radians according to the following equation:

$$\varphi=2\arccos\left(\frac{\Delta R}{2R}\right),\quad 0\le\Delta R\le 2R. \qquad (4)$$

According to expression (4), when $\Delta R=0,1R$, the detection areas will overlap by 93%, and when $\Delta R=0,5R$, they will overlap by 68%. As we can see, even with a relatively large displacement of the UAV, the degree of intersection of the detection areas will be quite high, which will ensure a smooth change in the density function (2).

In polar coordinate system, the calculation of the integral (2) is significantly simplified:

$$\Lambda_{Ri}=\int\limits_{-R}^{R}dx\int\limits_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}}\lambda\left(x-x_i,y-y_i\right)dy=$$
$$=\int\limits_{0}^{2\pi}d\varphi\int\limits_{0}^{R}R\lambda\left(R\right)dR, \qquad (5)$$

where

$$x=R\cos\varphi,\quad y=R\sin\varphi\quad\text{and}\quad dxdy=Rd\varphi dR. \qquad (6)$$

If the density of RF emitters distribution is specified as a set of points $\{x_k,\, y_k\}$ describing the coordinates of RF emitters placement in spectrum sensing area, their number falling within a circle with radius R is calculated using the following equation:

$$N_{ei}=\mathop{\#}\limits_{k=1}^{M}\left(\sqrt{\left(x_i-x_k\right)^2+\left(y_i-y_k\right)^2}\le R\right), \qquad (7)$$

where
– designation of the number count;
M – total number of RF emitters within spectrum sensing.

For the general case of RF emitters placement on a plane, it can be represented as a nonhomogeneous Poisson point process or Cox process, which is a generalization of the Poisson process, and for which the density function is random [20–22]. Then the probability density distribution of RF emitters number N_{ei} falling within an area S can be written according to the expression describing the Poisson distribution [23]:

$$p\left(N_{ei},\Lambda_{Ri}\right)=\frac{\Lambda_{Ri}^{N_{ei}}}{N_{ei}!}e^{-\Lambda_{Ri}}. \qquad (8)$$

This density depends on the position of circle center (x_i, y_i coordinates) with radius R in spectrum sensing area. We will seek the estimate of the maximum value of RF emitters number N_{emi} for each position of the UAV in spectrum sensing area as the quantile of the Poisson distribution of a certain level α, for example 0.99 (0.95 or 0.9) according to the following equation [24]:

$$P_{\alpha}\left(N_{ei}\le N_{emi}\right)=\sum_{l=0}^{N_{emi}}\frac{\Lambda_{Ri}^{l}}{l!}e^{-\Lambda_{Ri}}=$$
$$=\frac{\Gamma\left(N_{emi}+1,\ \Lambda_{Ri}\right)}{N_{emi}!}=\alpha,\quad N_{emi}\in\mathbb{N}, \qquad (9)$$

where $\Gamma(,)$ – incomplete Gamma-function.

The value of the expected maximum number of RF emitters calculated according to this equation will provide a reliable estimate of the required throughput capacity of RF sensor.

It is quite difficult to express the value of N_{emi} in analytical form from equation (9). Figure 2 shows the numerically obtained dependence of the maximum number of RF emitters N_{emi} on the value of the density function Λ_{Ri}.

The approximation of the dependence of N_{emi} Poisson distribution quantile value on parameter corresponding to the density function Λ_{Ri}, shown in Fig. 2, can be described by the following polynomial:

$$N_{emi}\left(\Lambda_{Ri}\right)=\sum_{n=0}^{4}a_n\Lambda_{Ri}^{n}, \qquad (10)$$

where the values of the coefficients a_n for some α are given in Table 1.

Approximation of a fourth-degree polynomial (10) is sufficient for calculating any values of N_{emi} for any Λ_{Ri}.

Table 1 Values of polynomial coefficients for expression (10)

α	a_0	a_1	a_2	a_3	a_4
0,99	3,201	1,542	-8,988 $\cdot 10^{-3}$	9,213 $\cdot 10^{-5}$	-3.567 $\cdot 10^{-7}$
0,95	2,266	1,352	-5,115 $\cdot 10^{-3}$	4,710 $\cdot 10^{-5}$	-1,661 $\cdot 10^{-7}$
0,9	1,361	1,307	-5,193 $\cdot 10^{-3}$	5,274 $\cdot 10^{-5}$	-2,000 $\cdot 10^{-7}$

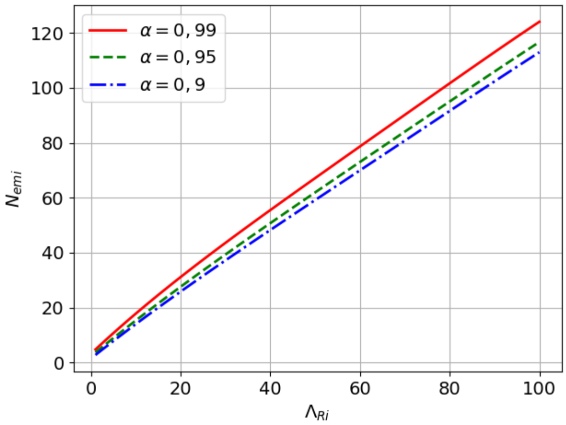


Fig. 2. Dependence of maximum RF emitters number N_{emi} on Λ_{Ri}

Thus, knowing the density of RF emitters distribution and the detection radius of a typical emitter R, it is possible to estimate the maximum number of emitters that can enter the detection region of RF sensor.

This estimate is the upper limit of maximum number of RF emitters. Since not all emitters that fall within the energy accessibility region of RF sensor emit radio signals simultaneously, the number of active emitters at any given moment will be less than the maximum. This number depends on the average intensity of their emission. Therefore, at any given moment, only a fraction of the maximum possible number of emitters will radiate RF signals.

2 RF signals flow modeling

We will consider a single-channel RF sensor, for which one receiver is connected sequentially to N_{ant} directional antennas. In [5], it is shown that for a channel with small-scale fading, which is typical for spectrum sensing using UAVs, time for signal analysis in the receiver band can be calculated using the following equation:

$$T_a \approx \frac{c}{20 N_{ant} \upsilon_{max} f_{\max}}, \tag{11}$$

where
c – speed of light;
υ_{max} – UAVs' maximum speed;
f_{max} – maximum frequency of analyzed bandwidth $\Delta\Pi$.

Then, the time required to scan the entire $\Delta\Pi$ band with a single-channel receiver with an instantaneous bandwidth ΔF when connecting N_{ant} antennas sequentially (without taking into account the time required to switch them) is:

$$T_A \approx T_a N_{ant} J, \quad J = \left\lfloor \frac{\Delta\Pi}{\Delta F} \right\rfloor . \tag{12}$$

Let us consider the signal flow in instantaneous bandwidth of RF sensor, where are N_{ij} RF emitters in j-th band, and

$$\sum_{j=1}^{J} N_{ij} = N_{emi} \ . \tag{13}$$

For each instantaneous bandwidth, the signal flow is a random process. We assume that all RF emitters radiate independently. Therefore, the start and stop times, as well as the duration of radiation of each emitter, are random variables with an exponential distribution [24]. The randomness of the time parameters of signals is also due to the influence of small-scale fading and shadowing during the movement of UAV relative to emitters.

We will describe the operation of RF emitter in the i-th detection region using a nonhomogeneous Poisson process with some random intensity $\lambda_k(t)$, $k = 1, 2, \ldots, N_{emi}$, which characterizes the intensity of RF emitter radiation. Then, the average number of events corresponding to the beginning or stopping of radiation for the i-th emitter in a time interval T_a will be:

$$\Lambda_k\left(T_a\right) = \int_0^{T_a} \lambda_k\left(t\right) dt. \tag{14}$$

To estimate the required throughput capacity of RF sensor, we are interested in how many RF emitters will be active in time interval $T_a = t_2 - t_1$, i.e., at least one signal fragment will be observed in this time interval. We will denote the number of separate emitter radiation session as n_e. Possible cases of time intervals of RF emitter radiation are shown in Fig. 3.

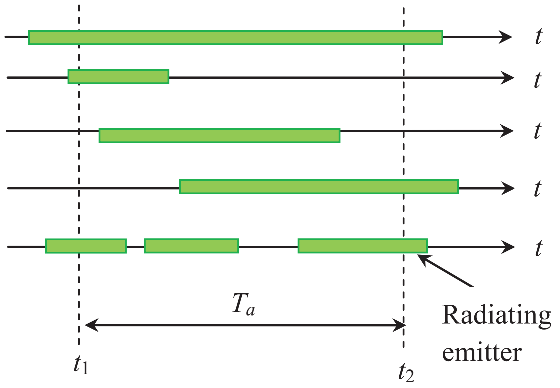


Fig. 3. Time intervals of RF emitters activity

The probability that RF emitter will radiate at least once during the time interval T_a is calculated using the following equation:

$$P\left(n_e \geq 1, \Lambda_k\left(T_a\right)\right) = 1 - \frac{\left(\Lambda_k\left(T_a\right)\right)^0}{0!} e^{-\Lambda_k\left(T_a\right)} = \\ = 1 - e^{-\Lambda_k\left(T_a\right)}. \quad (15)$$

Figure 4 shows the time-frequency of scanning the analyzed frequency band $\Delta\Pi$ for the case of using three antennas $N_{ant} = 3$, which are sequentially switched to one receiver. The instantaneous bandwidth of the receiver for the given diagram is four times smaller than the analyzed frequency band. All frequency bands with a width of ΔF are scanned sequentially. In one band, signal analysis is performed during N_{ant} time intervals, each lasting T_a. When using a multi-channel signal processing scheme, where each antenna is connected to a separate receiver, the analysis time is reduced by N_{ant} times.

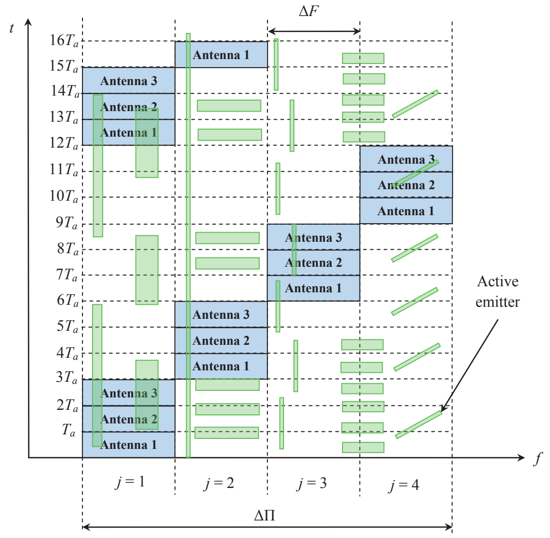


Fig. 4. Time-frequency diagram of frequency band scanning

Since RF emitters radiate independently, using the superposition principle for Poisson processes, the average number of broadcasts of all N_{emi} emitters in the i-th position of the UAV at time interval T_a can be written as follows:

$$\Lambda_{Ti} = \sum_{k=1}^{N_{emi}} \Lambda_k\left(T_a\right) = \sum_{k=1}^{N_{emi}} \int_0^{T_a} \lambda_k\left(t\right) dt. \quad (16)$$

Then, similarly to expression (15), the probability that all N_{emi} emitters will be active in the i-th position of the UAV during time T_a will be:

$$P\left(N_{emi}, \Lambda_{Ti}\right) = 1 - e^{-\Lambda_{Ti}}. \quad (17)$$

Then, the maximum number of RF emitters N_{max} that will fall within a circle with area S across the entire search area can be estimated using the following equation:

$$N_{max} = \underset{N_{emi}}{\operatorname{argmax}} \left(P\left(N_{emi}, \Lambda_{Ti}\right)\right) P\left(N_{emi}, \Lambda_{Ti}\right). \quad (18)$$

3 Estimating the required throughput capacity of RF sensor

Thus, the method for calculating the required throughput capacity of the RF sensor consists of the following steps:

1) calculate maximum number of RF emitters that fall into i-th region of energy accessibility according to equation (10);

2) estimate average number of active emitters in i-th region of energy availability according to equation (16);

3) calculate probability of location the maximum number of emitters in i-th region in an active state according to equation (17);

4) determine maximum number of simultaneously active emitters in i-th region according to equation (18);

5) calculate required throughput capacity of RF sensor as the ratio of maximum number of RF emitters that may be in circle of radius R when flying over a given sensing area to analyzed time T_a according to the following equation:

$$\gamma = N_{max}/T_a\,. \quad (19)$$

Estimation throughput capacity in accordance with the above methodology requires a large amount of a priori information about density of RF emitters distribution and their activity. Therefore, when discussing the results of mathematical modeling, there will be made assumptions for calculations under conditions of a priori uncertainty.

4 Results of mathematical modeling and discussions

We will use the Python programming language to model the process of estimating the required throughput capacity of RF sensor. The parameter values for modeling are given in Table 2.

Table 2 Parameters values of UAV based RF sensor

Parameter	Value
R, km	10
υ_{max}, m/s	30
f_{max}, GHz	6
N_{ant}	6
ΔF, MHz	50
$\Delta\Pi$, GHz	5,5
T_a, ms	0,138
$\Delta R = 0,5R$, km	5
α	0,95

We will model the density of RF emitters distribution as a nonhomogeneous Poisson point process [25] in a square with sides of 100 km by 100 km using a mixture of four two-dimensional normal distributions according to the following equation:

$$\rho\left(x,y\right) = \sum_{i=1}^{4} b_i e^{-\frac{(x-x_i)^2+(y-y_i)^2}{\sigma_i^2}}, \qquad (20)$$

where values of density parameters are given in Table 3.

Table 3 Values of parameters for the expression (20)

i	b_i, km	x_i, km	y_i, km	σ_i, km
1	0,25	15	15	20
2	0,25	-20	-30	15
3	0,5	35	-35	10
4	0,1	-35	-25	15

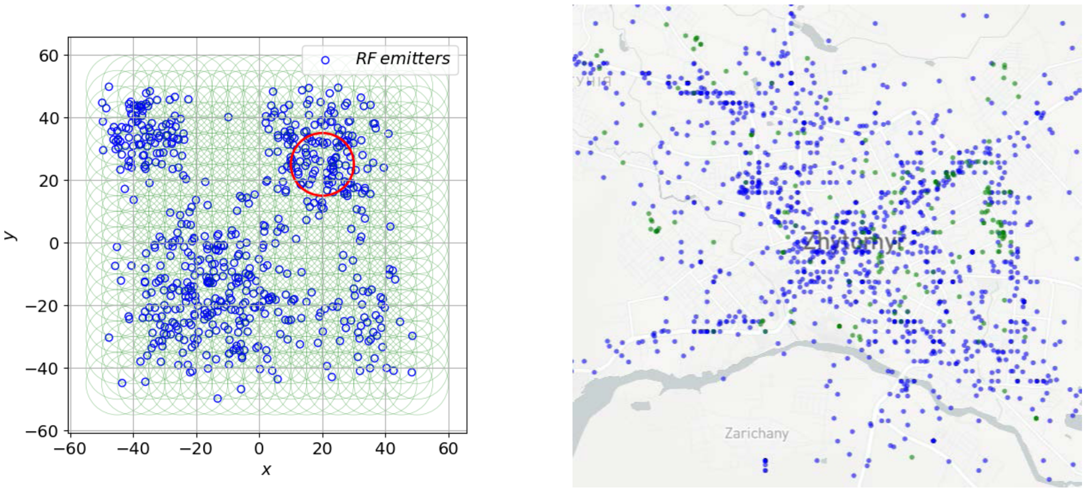
The density of emitters location, the area of their energy availability (marked with green circles), and the area for which the throughput capacity is calculated (marked with a red circle) are shown in Fig. 5a. The total number of emitters in the spectrum sensing area is $M = 630$. In Fig. 5b is depicted real locations of 1732 cell towers in one of Ukrainian regions from [26]. As we can see in first approximation simulated data correspond to real life data.

We assume that when switching directional antennas to the receiver, only level of received signal from each emitter will change due to anisotropy of antenna's directional pattern, and the number of emitters will remain unchanged. That is, in each of antennas, signal level will exceed the detection threshold. Then, the signal flow from the m-th emitter will be described according to the following equation [25]:

$$\lambda_m(t) = d_m\left[1 + \sin\left(c_m t\right)\right], \quad m = 1, \ldots, M, \qquad (21)$$

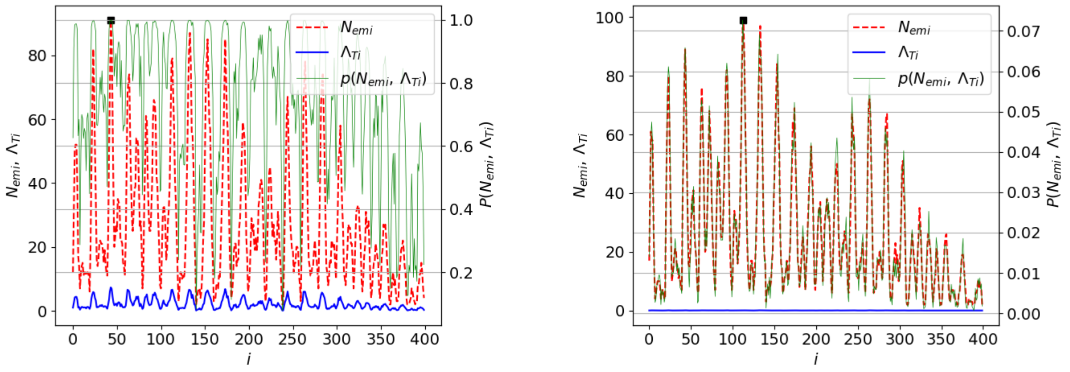
where d_m, c_m – uniformly distributed random variables.

Figure 6 shows the dependencies of maximum number of emitters N_{emi} into the i-th circle with radius R when UAV moves, as well as the average number of emitters Λ_{Ti} that will be active during time T_a within detection area, and probability value $P(N_{emi}, \Lambda_{Ti})$.



(a) (b)

Fig. 5. Area of detection of RF sensor and simulated density of emitters location (a) and real data of cell towers in one of Ukrainian regions (b)



(a) (b)

Fig. 6. Dependencies of N_{emi}, Λ_{Ti} and $P(N_{emi}, \Lambda_{Ti})$ of UAVs' position i for $d_m = T_a$ (a) and $d_m = 0,01T_a$ (b)

Maximum number of emitters that can simultaneously radiate within a given sensing area in time interval T_a is 84 and is marked with a black square in Fig. 6. Then, the required throughput capacity of RF sensor, calculated according to equation (19), is $\gamma = 6,08 \cdot 10^5$ RF emitters (channels) per second for $d_m = T_a$ (Fig. 6a) and $\gamma = 5,2 \cdot 10^4$ RF emitters for $d_m = 0,01T_a$ (Fig. 6b).

In practice, a priori descriptions of emitters distribution densities and signal flow intensity from them are often not available. Therefore, in absence of a priori information, it is advisable to make the following assumptions:

1) emitters distribution density is homogeneous Poisson point process throughout sensing area with a maximum value of parameter λ_R;

2) the intensity of emitters radiation is a stationary Poisson process, with maximum value of parameter λ_T, which is the same for all emitters in sensing area.

In this case calculation of required throughput capacity of RF sensor is greatly simplified as there is no need to search spatial and temporal densities of RF emitters. It is expected that in this case we will need greater throughput capacity as in case of nonhomogeneous Poisson processes with the same maximal parameters values.

Conclusions

The scientific novelty of the obtained results includes improved mathematical models of RF emitters distribution density on a plane and the flow of signals from them using nonhomogeneous Poisson processes. It was also developed a methodology for estimating the required throughput capacity of UAV based RF sensor. Obtained results may be used when designing RF sensors for small UAVs, particularly in establishing requirements for their throughput capacity. Prospects for further research in this area are development of structures and algorithms for single-channel and multichannel UAV based RF sensors.

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Оцінювання необхідної пропускної здатності засобу радіомоніторингу для безпілотного літального апарата

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Використання малорозмірних безпілотних літальних апаратів (БпЛА) для ведення радіомоніторингу (РМ), особливо в урбанізованій місцевості, володіє рядом переваг порівняно із використанням наземних засобів виявлення та оцінювання параметрів сигналів джерел радіовипромінювання (ДРВ). Для розроблення засобів РМ для БпЛА необхідно сформувати ряд вимог до нього. Однією із основних є необхідна пропускна здатність. Метою статті є удосконалення методичного апарату для формування вимог до розміщених на БпЛА засобів РМ. Для опису щільності розподілу ДРВ запропоновано використовувати неоднорідний просторовий процес Пуассона у поєднанні із параметричними або непараметричними функціями розподілу. Функція щільності даного розподілу відображає середню кількість ДРВ, що знаходяться в межах енергетичної доступності, і можуть бути виявлені. Використання квантиля заданого рівня розподілу Пуассона, в якому як параметр використано функцію щільності, дозволяє оцінити максимальну кількість ДРВ. Потік сигналів від окремих ДРВ описано за допомогою неоднорідного процесу Пуассона. Моменти часу виходу в ефір та тривалість випромінювання сигналів підпорядковані експоненціальному розподілу. Отримано оцінки середньої інтенсивності виходу в ефір ДРВ протягом інтервалу аналізу заданої смуги частот для одноканальної багатоантенної системи. Наведено методику оцінювання необхідної пропускної здатності засобу РМ та рекомендації щодо використання запропонованого методичного апарату в умовах апріорної невизначеності щодо щільності розподілу ДРВ та інтенсивності потоку сигналів. Використання значень максимальної кількості ДРВ в межах енергетичної доступності за всією областю ведення РМ, середньої інтенсивності виходу в ефір ДРВ та часу аналізу миттєвої смуги частот дозволило отримати оцінку необхідної пропускної здатності засобу РМ.

Ключові слова: джерело радіовипромінювань; радіомоніторинг; пропускна здатність; процес Пуассона; щільність просторового розміщення; потік сигналів; безпілотний літальний апарат