Advances in Military Technology
Vol. 17, No. 2, 2022, pp. 341-356
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01739

Bounds Calculation Method of Electromagnetic Availability Zone of Radio Emission Source

V. Maliuk[1], O. Iohov[1], S. Horielyshev[1*], V. Olenchenko[1], O. Oleschenko[2], O. Novykova[1] and K. Tkachenko[1]

[1] *National Academy of National Guard of Ukraine, Kharkiv, Ukraine*
[2] *Main Directorate of the National Guard of Ukraine, Kyiv, Ukraine*

The manuscript was received on 1 June 2022 and was accepted after revision for publication as research paper on 22 October 2022.

Abstract:

The article deals with the problem of determining the electromagnetic availability zone of the radio transmitter of the radio communication channel in the UHF/VHF range on the terrain map of the area. This problem was solved using well-known mathematical models of radio signal propagation, depending on the characteristics of the specific area. Based on the wave algorithm, a bounds calculation method of electromagnetic availability zone is proposed, using a digitized radiation pattern of radio means. The conducted calculations show the effectiveness of the method in the tasks of assessing the performance of a mobile radio communication channel and its security at local combat operations in the conditions of operation of an enemy radio reconnaissance receiver or a radio interference system.

Keywords:

electromagnetic availability zone, enemy radio reconnaissance receiver, interference immunity, mobile radio communication channel, radio station, wave algorithm

1 Introduction

Clarifying the range of the UHF/VHF radio source is an important issue in the tasks of organizing the mobile radio communication channel operation, especially when conducting local combat operations by tactical units, among which are the following [1-4]: analysis of the radio communication channel operability conditions, decrease in the effectiveness of enemy radio reconnaissance, and protection of the radio channel from the radio interference system.

In all these tasks, the common point is the use of the concept of electromagnetic availability (EMA) zone of a radio emission source. Under the EMA zone of a radio

* *Corresponding author: Scientific and Research Center of Service and Military Activities of the National Guard of Ukraine, Kharkiv, National Academy of National Guard of Ukraine, Zakhysnykiv Ukrainy sq., 3, UA-61000 Ukraine. Phone: +380 67 959 91 53, E-mail: port_6633@ukr.net. ORCID 0000-0003-1689-0901.*

transmitter we will understand the set of points in space at which this transmitter provides the minimum required radio signal power at the input of the corresponding receiver, depending on its sensitivity.

Based on certain provisions of the electromagnetic field theory and the tensor calculus theory, in the papers [3-4] a mathematical model of the EMA in a military radio communication system is proposed. It is based on the representation of the modeling object by a quasi-crystal. These papers also offer a geometric interpretation of the EMA of a separate military radio station as an indicator of the level of its radio masking. The results obtained by the authors are of a theoretical nature and have not yet received practical application in solving the problems of organizing the operation of mobile radio communication systems.

For the case of strongly rugged terrain, the paper [5] proposes a method for estimating the EMA zone by radio monitoring means, which allows to simulate various options for constructing regional subsystems of radio frequency monitoring with sufficient accuracy for practice. The parameters of the calculated EMA zone of radio monitoring means depend on the power and radiation pattern (RP) of the transmitter antenna, the distance between the transmitter and the receiver, the terrain, and the sensitivity of the receiver. The algorithm for calculating the boundaries of the EMA zone of radio monitoring means, which determines the points of intersection of lines of equal heights with the current azimuth on the terrain map, refines the boundary of the EMA zone in an iterative way. This causes its high labor intensity. So, according to [5], the time spent on the calculation of one EMA zone, depending on the relief, the built-up area and the discreteness of readings in azimuth, is from 15 to 120 minutes.

When conducting combat operations on lightly rugged terrain by tactical units, a mobile radio communication channel is usually characterized by low transmitter powers (1-5 W) and, accordingly, by a short range (up to 5-6 km) [6]. This allows to use simpler mathematical models of radio signal propagation. These models make it possible to calculate the average value of the attenuation of the radio signal depending on the characteristics of a particular area and speed up the calculation of the boundaries of the EMA zone of the radio emission source.

So, in ideal conditions of free space, the power loss of a radio signal can be estimated using the simplest Friis propagation model [7]:

$$P_{\mathrm{R}} = P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}} \left(\frac{\lambda}{4\pi d} \right)^2 \tag{1}$$

where P_{R} – the power [W] received by the antenna at a distance d [m],

P_{T} – the signal transmitter power [W],

G_{T} and G_{R} – the antenna gains of the transmitter of the radio signal in the direction of the receiver and the receiving antenna in the direction of the radio transmitter, respectively,

λ – the wavelength [m].

Passing to the logarithmic scale, for isotropic antennas relation Eq. (1) can be represented in the following form:

$$P_{\mathrm{R}} = P_{\mathrm{T}} - L_{\mathrm{P}}, \text{ [dB]} \tag{2}$$

where L_{P} – the radio signal power transmission losses, which in free space according to [8] are calculated

$$L_P = 32.44 + 20\log F_{MHz} + 20\log D_{km}, \text{ [dB]} \tag{3}$$

where F_{MHz} – the radio signal frequency [MHz],

D_{km} – the distance between transmitter and receiver [km].

When conducting combat operations on a smooth hilly terrain with an average height of irregularities up to 15 m, it is advisable to use the well-known Egli statistical model [9]. The model neither includes diffraction losses caused by radio signal propagation over rugged terrain, nor does it take into account the presence of some vegetation obstacles such as, trees or shrubs. In contrast to Eq. (3), the radio signal power losses are defined here as follows [10]:

$$L_P = 20\log F_{MHz} + 40\log D_{km} - 20\log h_T + \begin{cases} 76.3 - 10\log h_R, & h_R \le 10 \\ 85.3 - 20\log h_R, & h_R > 10 \end{cases}, \text{ [dB]} \tag{4}$$

where h_T, h_R – the effective antenna height of transmitter and receiver, respectively [m].

The conditions of urban developments and suburbs correspond to more complex models by Okumura, Hata and others [10-12]. To build a simple and fast method for calculating the boundaries of the EMA zone of radio means of a mobile radio communication channel, we restrict ourselves to the simplest calculated relationships of radio signal power losses Eq. (3) or Eq. (4). As necessary, depending on the characteristics of the particular terrain and factors that need to be taken into account, the relationships of radio signal power loss can be replaced by more complex ones.

The aim of the study is to develop a bounds calculation method of the EMA zone of radio emission sources as part of a UHF/VHF mobile radio communication channel with reference to a topographic terrain map with a tactical situation.

To achieve this aim, it is necessary to solve the following tasks:

- to obtain mathematical relationships for determining the zones of electromagnetic availability of radio emission sources as part of a mobile radio communication channel, taking into account the losses of radio signal power,
- to propose a fast and reliable algorithm for determining the bounds of the EMA zone of transmitters of a mobile radio communication channel,
- using practical calculations on a topographic terrain map with a tactical situation, to check the feasibility of applying the bounds calculation method of the EMA zone of radio emission sources in the tasks of organizing the operation of a mobile radio communication channel.

2 Determination of Electromagnetic Availability Zones of a Radio Emission Sources of a Mobile Radio Communication Channel

Let us analyze the interaction of radio means of a mobile radio communication channel, taking into account the range of radio emission sources. Let us denote the area of the topographic terrain map with a tactical situation as Ω. The model of a mobile radio communication channel, proposed by the authors for consideration, in the general case contains the following objects (Fig. 1).

Object 1 is a ground-based UHF/VHF radio signal receiver/transmitter with transmitter power P_1 at the point with coordinates $(x_1, y_1) \in \Omega$. The digitized normalized antenna radiation pattern is described by the function $G_1(\theta)$, antenna's own azimuth of the radiation pattern makes up the angle θ_1.

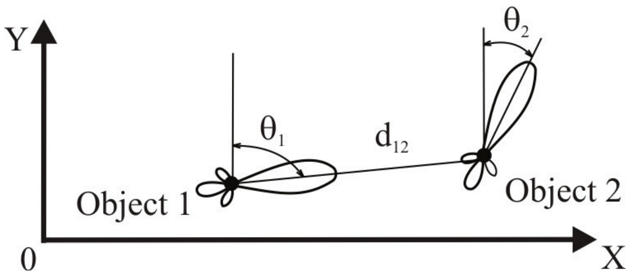
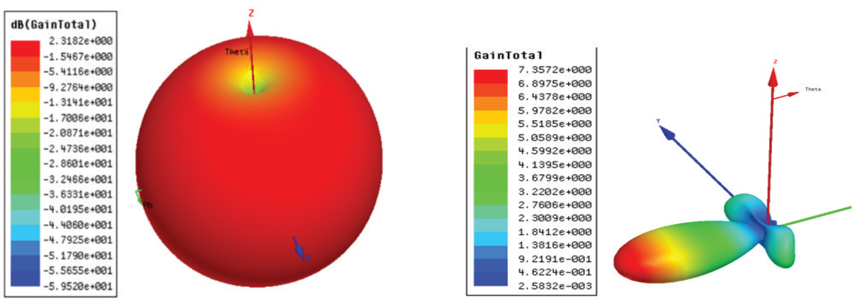


Fig. 1 Mobile radio communication channel objects

Object 2 is a ground-based UHF/VHF radio signal receiver/transmitter with transmitter power P_2 at the point with coordinates $(x_2,\ y_2) \in \Omega$. The digitized normalized antenna radiation pattern is described by the function $G_2(\theta)$, the antenna's own azimuth of the radiation pattern makes up the angle θ_2.

The sensitivity of the receivers of both objects will be considered the same and equal to E_s, [µV].

The digitized antenna radiation pattern of a mobile radio communications means $G(\theta)$ can be calculated using the program for modeling three-dimensional electromagnetic fields [13]. The Fig. 2 [2] shows examples of calculating the RP of omnidirectional and directional antennas of mobile radio communications means.



a) b)

Fig. 2 Examples of digitized antenna radiation patterns used in the mobile radio communication channel model a) the RP shape of an omnidirectional antenna device, b) the RP shape of a directional antenna device [2]

Let obtain a relationship that determines the boundary of the EMA zone of the transmitter of object 1, which interacts with the receiver of object 2. For mobile radio communications means, when a matched antenna is connected directly to the input of a receiver that has sensitivity E_s and a matched active input resistance R_A, the following relationship takes place [14]:

$$P_{\min} = \frac{E_s^2}{4R_A} \tag{5}$$

The value $P_{\min}$ determines the minimum useful signal power required for high-quality receiving at the receiver input of object 2. For example, according to the source [6], in Mototrbo™ DP4000 radio stations the receiver sensitivity is 0.25 µV, and for the standard value R_A = 75 Ω, the minimum required value of the radio signal power is P_{min} = –126.8 dBm. It is logical to assume that at the boundary of the EMA zone of the transmitter of object 1, the power of the radio signal at the input of the receiver of object 2 should not be less than P_{min}.

In accordance with Eq. (1), we determine the power of the useful signal of the radio transmitter of object 1 at the location of the radio receiver of object 2, taking into account the functions of the digitized RP of antennas:

$$P_{12}(x_2, y_2) = P_1 G_1(\theta_{12} - \theta_1) G_2(\theta_{21} - \theta_2) \left(\frac{\lambda}{4\pi \mathrm{d}_{12}} \right)^2 \tag{6}$$

where P_{12} – the power of the signal received by the antenna of the radio receiver of object 2 [W],

P_1 – the power of the signal from transmitter of the object 1 (W),

θ_{12} – the azimuth angle from object 1 on object 2,

θ_{21} – the azimuth angle from object 2 on object 1,

$d_{12} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$ – the distance from object 1 to object 2.

To determine the EMA zone of the transmitter of object 1, it is advisable to orient the directional antenna of the receiver of object 2 to object 1 in azimuth, setting $\theta_2 = \theta_{21}$. In this case, the normalized function of the receiver antenna RP takes on the maximum value $G_2(0) = 1$. Calculating the signal powers P_{12} and P_1 in [dBm], on a logarithmic scale we get

$$P_{12}(x_2, y_2) = P_1 + 10 \log\left[G_1(\theta_{12} - \theta_1)\right] - L_\mathbf{P} \quad , \text{[dBm]} \tag{7}$$

Thus, the EMA zone of the object's 1 transmitter for the receiver of object 2 with the minimum required useful signal power P_{min} can be defined as

$$\Omega_{E_1} = \left\{ \forall (x_2, y_2) \in \Omega \mid P_{12}(x_2, y_2) \geq P_{min} \right\} \tag{8}$$

The EMA zone of the transmitter of object 2 for the receiver of object 1 can be determined in the same way:

$$\Omega_{E_2} = \left\{ \forall (x_1, y_1) \in \Omega \mid P_{21}(x_1, y_1) \geq P_{min} \right\} \tag{9}$$

where

$$P_{21}(x_1, y_1) = P_2 + 10 \log\left[G_2(\theta_{21} - \theta_2)\right] - L_\mathrm{P} \quad , \text{[dBm]} \tag{10}$$

The general condition for the operability of a mobile radio communication channel involves the simultaneous placement of receivers of objects 1 and 2 in adjacent EMA zones of radio channel transmitters:

$$\begin{cases} (x_1, y_1) \in \Omega_{E_2} \\ (x_2, y_2) \in \Omega_{E_1} \end{cases} \tag{11}$$

From the obtained relations Eq. (7)-(11) it follows that the size of the EMA zone and the fulfillment of the conditions for the operability of a mobile radio communication channel depend on their power, the orientation of the antenna radiation pattern, power losses along the signal propagation path and the sensitivity of the radio signal receiver.

3 Algorithm for Determining the Bounds of the Electromagnetic Availability Zone of a Radio Emission Source

To construct an algorithm for determining the bounds of the EMA zone of a radio emission source Eq. (8), we use the modification of the wave algorithm given in the work [2].

We will consider the pixel matrix of the image of a topographic terrain map with a tactical situation as a discrete working field, limited by the coordinates x_{min}, x_{max}, y_{min}, y_{max}. The state of the field cells defines the Mask array as array[x_{min} .. x_{max}, y_{min} .. y_{max}] of boolean. A free cell of the field with coordinates (x, y) corresponds to the Mask[x, y] = False state. A non-free cell of the field with coordinates (x, y) corresponds to the Mask[x, y] = True state. The coordinates of the points of the old and new wave fronts are accumulated respectively in the Front array (as array[1…Lf] of record x, y: integer end) and Fnew array (as array[1…Lfnew] of record x, y: integer end).

The modification of the algorithm from [2] is shown in the Fig. 3. The algorithm consists of three stages: initialization, wave propagation and formation of an array of zone border coordinates Eq. (8).

The initialization stage (block 1) consists in determining the properties of the cells of the discrete working field (all cells are free). The transmitter location point (x_1, y_1), should be chosen as the starting cell, so the corresponding element of the mask array changes its value Mask[x_1, y_1] = True. The coordinates of the starting cell are also written to the Front array. The length of the wave front is Lf = 1.

The stage of wave propagation (blocks 2...14) consists in cyclic updating of Fnew, Front, and Mask arrays. In block 2, the flag for the end of the wave propagation stage is Stop = True. Next, the cycle scanning the points of the old Front is performed (blocks 3, 11, 12, cycle parameter i). For each point of the old wave front, a scanning cycle of nearby points is performed (blocks 4, 9, 10, cycle parameter j) using working arrays DX (0,1,0, −1) and DY (−1,0,1,0) (block 5). If a candidate point with coordinates (x, y) is free (block 6) and the condition Eq. (8) is satisfied (block 7), then the candidate point with coordinates (x, y) is included in the new front (block 8). Here, the length of the new wave front Lfnew is increased by 1, the coordinates of the current map point are entered into the array Fnew, the corresponding element of the Mask[x, y] array is set to True, and the flag for the end of the wave propagation stage is Stop = False.

At the end of the cycle of polling nearby points, the Fnew array is rewritten to the Front array, the length of the new wave front Lfnew is set to zero (block 13). The wave propagation process ends at the zone boundary, when the condition Eq. (8) ceases to be satisfied for any candidate points. In this case, the Stop flag switches to the next stage of the algorithm.

Attention should be paid to the rule for deciding whether the current point of the discrete working field belongs to the EMA region of the radio emission source in block 7. The transition from the Friis radio signal propagation model to the Egli model in this block is easily done by taking into account relations Eqs (3) or (4), respectively, in Eqs (7) and (8).

The next step of the algorithm is the stage of laying the boundaries of the zone. After resetting the counter of border points of the zone L_i (block 15), the points of the working area of the map x_{min}, x_{max}, y_{min}, y_{max} are scanned using the Mask array (blocks 16...30). For each point with coordinates (x, y), four nearby points are checked to make sure their bit mask is set to True. The number of such suitable nearby points is accumulated in a Pixels counter (blocks 21 and 22). If for the current point (x, y) the value of the Pixels counter lies in the range from 1 to 3, then this point is included in the zone boundary Eq. (8) and stored in the Border array – array of coordinates of the zone boundary points (blocks 25 and 26).

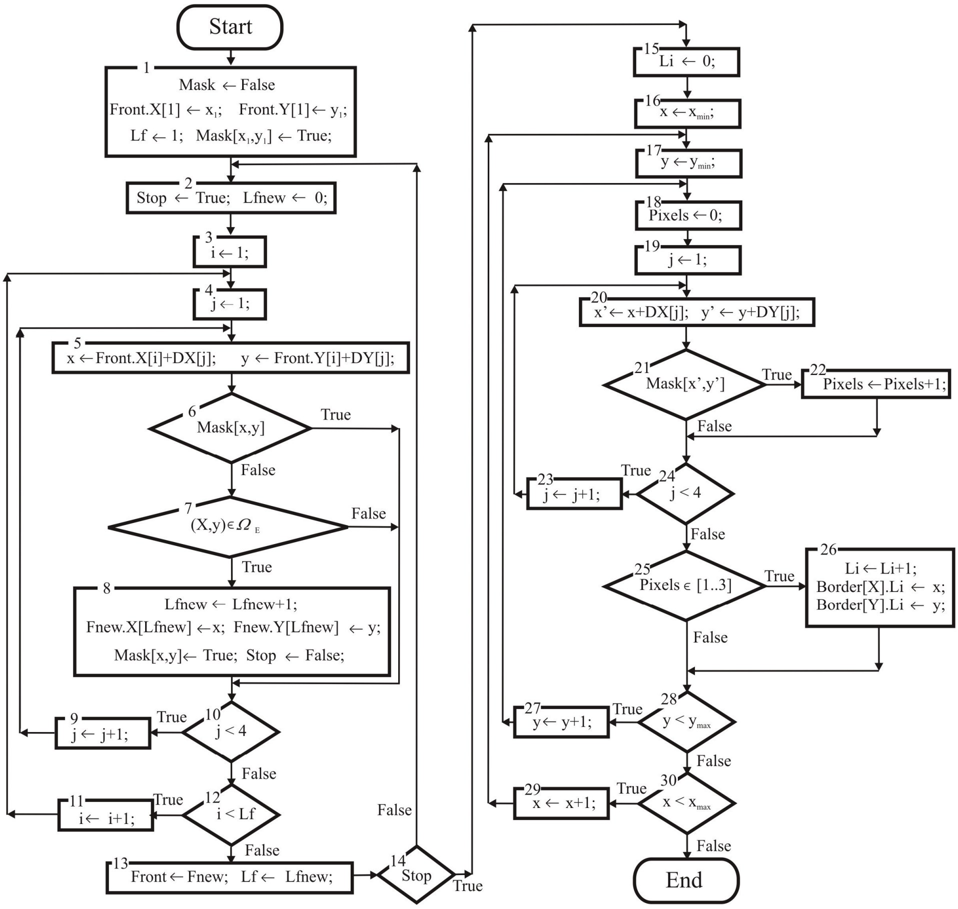


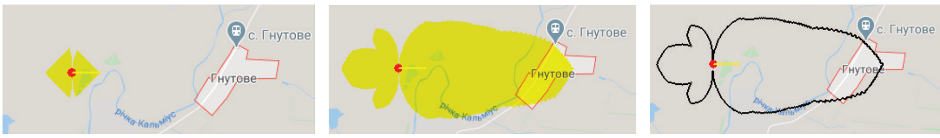
Fig. 3 Algorithm for calculating the bounds of the electromagnetic availability zone of a radio emission source

The Fig. 4 shows the main stages of the algorithm (Fig. 3), which are obtained by the authors, in the problem of calculating the boundary of the transmitter's EMA zone in relation to the terrain map.

Fig. 4a shows the beginning of the wave propagation from the transmitter location (x_1, y_1). For clarity, map points for which the corresponding element of the Mask array is set to True are colored yellow. The ending of the wave propagation stage is shown in Fig. 4b. Here the Stop flag is set to True. The stage of laying the boundaries of the Ω_E zone is illustrated in Fig. 4c.

The scale of the map taken from Google Maps is 19 m/pixel. The calculations were made for a transmitter with a power of 1 W operating at a frequency of 446 MHz and for a receiver sensitivity of 0.25 μV.

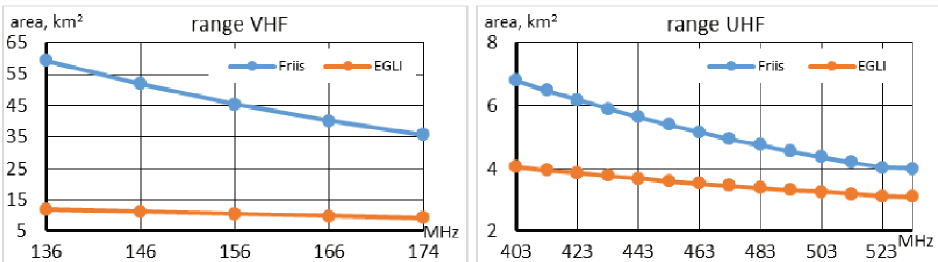
The maximum distance from the transmitter location point to the EMA boundary points corresponds to the main lobe of the antenna RP and equals 3.629 km. By counting the number of cells in the Mask array with the True state and binding to the map scale, it is additionally possible to estimate the area of the resulting zone Ω_E of the transmitter. So, in the example above, the area of the zone Ω_E is equal to 5.56 km^2, which is 3 % of the total area of the topographic terrain map with a tactical situation Ω. Practical calculations show that with an increase in the sensitivity of the radio receiver by 0.05 μV, the area of the EMA zone increases by 1.56 times.



a) b) c)

Fig. 4 Stages of the algorithm for calculating the bounds of the EMA zone of a radio emission source a) the beginning of wave propagation b) the ending of wave propagation c) laying the boundaries of the zone

The Fig. 5 shows the dependencies of the area of the EMA zone of the radio station Mototrbo™ DP4000 [5] on the signal frequency in the VHF (136-174 MHz) and UHF (403-527 MHz) bands. The calculations were carried out for the Friis and Egli signal propagation models. The calculation results show that with a decrease in the frequency of the radio signal, both in the VHF and UHF bands, the size of the EMA zone increases by 1.7 times for the Friis model and by 1.3 times for the Egli model. It should be noted that as the frequency increases in the UHF range, the sizes of the EMA zone obtained by different models tend to converge.



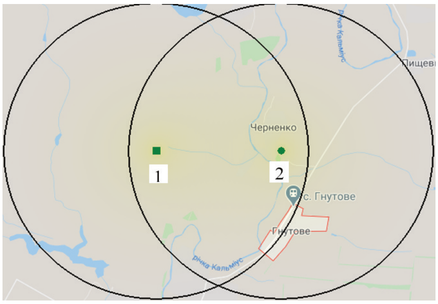
a) b)

Fig. 5 Dependence of the size of the EMA zone of the radio emission source on the signal frequency a) VHF band b) UHF band

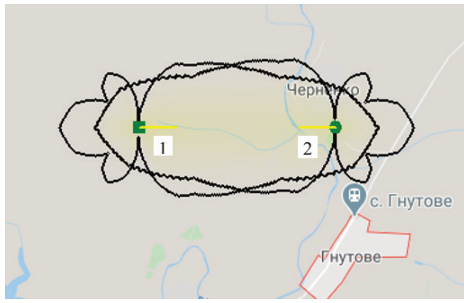
The calculation of EMA zones also makes it possible to evaluate the fulfillment of the conditions for the operability of a mobile radio communication channel Eq. (11). Two options for calculating adjacent EMA zones of an operable radio channel for omnidirectional and directional antenna systems are shown in the Fig. 6.

The results of calculations were obtained on the map of the area for the power of radio transmitters 1 W, the sensitivity of radio receivers $E_{s1} = E_{s2} = 0.25$ μV. Conditions for the operability of the mobile radio communication channel (Eq. 11) are satisfied for both options.

In addition to the analysis of operability conditions, the presence of EMA zones of radio means of a mobile radio communication channel should also be taken into account when they operate in the presence of foreign objects, such as radio reconnaissance receivers or deliberate enemy radio interference systems.



a)



b)

Fig. 6 Examples of calculation of EMA zones of mobile radio communications means a) for omnidirectional antennas b) for directional antennas

4 Calculating for the Range of Operation of Radio Means in the Conditions of Operation of an Enemy Radio Reconnaissance Receiver

Let us consider the operation of a mobile radio communication channel in the presence of an enemy radio reconnaissance receiver.

Suppose that the receiver/transmitter of object 1 has an omnidirectional antenna with RP $G_1(\theta) = 1$, and for object 2 – a directional antenna with RP $G_2(\theta)$. Let us designate the enemy radio reconnaissance receiver as object 3. Due to the lack of a priori information about the parameters of object 3, we can assume that it has an omnidirectional antenna with RP $G_3(\theta) = 1$. The variant of the layout of objects in the simulated situation is shown in the Fig. 7.

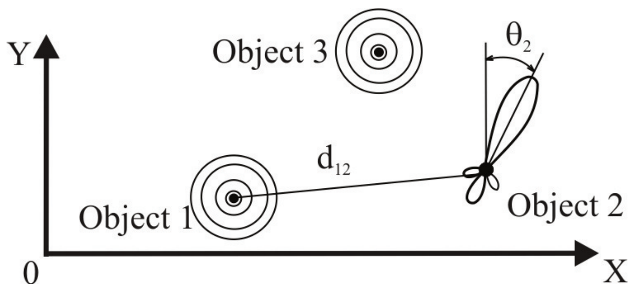


Fig. 7 Scheme of the operation of a mobile radio communication channel in the presence of an enemy radio reconnaissance receiver

The results of calculations on the map of the area of EMA zones of an operable mobile radio communication channel, obtained by authors for the power of radio transmitters $P_1 = P_2 = 1$ W, are shows in the Fig. 8. Calculations were made for two variants of the radio receivers sensitivity.

The first version of the calculations was obtained for the sensitivity of radio receivers of 0.25 μV, which is typical for mobile radio communications means. The calculated EMA zones of radio channel objects 1 and 2 are designated as Ω_{11} and Ω_{21}. The calculation results show that object 1 is located in the EMA zone of object 2 and vice versa, i.e. the mobile radio communication channel is operational. In addition, a foreign object 3 enters the EMA zone Ω_{11}, the radio receiver of which has the ability to listen to the useful signal of the radio transmitter 1. Object 3 does not fall into the EMA zone of object 2, designated as Ω_{21}, that is, radio transmitter 2 is not audible. The sizes of the zones Ω_{11} and Ω_{21} evaluate for 19 % and 3 %, respectively, of the total area of the operational space of the map.

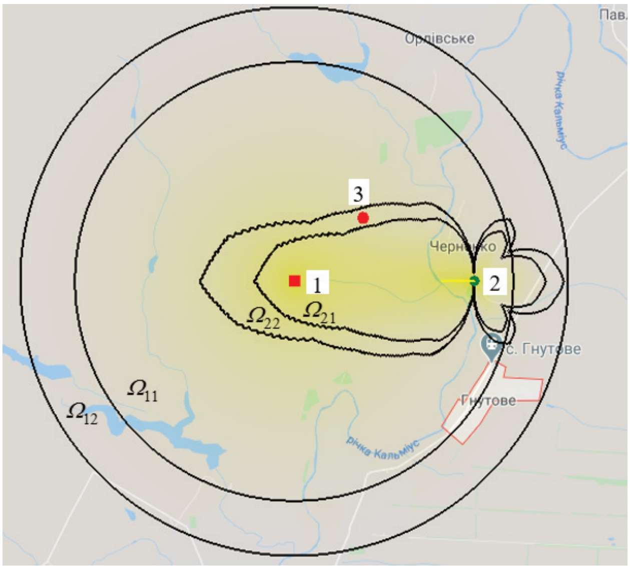


Fig. 8 Results of calculating electromagnetic availability zones of a mobile radio communication channel

The second version of the calculations was obtained for the sensitivity of radio receivers of 0.2 µV, which is typical for reconnaissance receivers. In this case, the calculated EMA zones of objects 1 and 2 are designated as Ω_{12} and Ω_{22}. The shape of the EMA is preserved, but the dimensions increase by 1.5 times, evaluating for 29 % and 5 %, respectively, of the total area of the operational space of the map. It should be noted that here the probability of listening to both objects of the radio channel increases, since object 3 is located both inside the zone Ω_{12} and Ω_{22}.

5 Calculating for the Operating Range of Radio Means in the Problem of Protecting a Radio Channel from an Enemy Radio Interference System

Consider taking into account the range of radio emission sources in the problem of protecting a radio channel from an enemy radio interference system [2, 15].

The UHF/VHF radio communication channel model, considered in [2, 15], contains objects (Fig. 9) with the following parameters:

Object 1 – the signal transmitter/receiver with omnidirectional antenna at a point with coordinates (x_1, y_1). The normalized antenna RP is described by function $G_1(\theta) = 1$. The power of transmitter is P_1, the sensitivity of radio receiver is E_{s1}.

Object 2 – the signal transmitter/receiver with a beam antenna system at a point with coordinates (x_2, y_2). The normalized antenna RP is described by $G_2(\theta)$ function obtained with calculation. The power of transmitter is P_2, the sensitivity of radio receiver is E_{s2}.

Object 3 – $N_i\left(x_{3_i}, y_{3_i}, P_{3_i}\right), i = 1\ldots K$, the radio interference source system with corresponding coordinates and radiation power. Radiation from radio interference sources is omnidirectional, therefore $G_{3_i}\left(\theta\right) = 1, i = 1\ldots K$.

The purpose of the calculations is to determine the bounds of the maximum size zone Ω_s of stable radio receiving in the UHF/VHF band for mobile radio communications means with directional antennas under the action of several terrestrial sources of additive frequency-concentrated radio interference $N_1 \ldots N_K$.

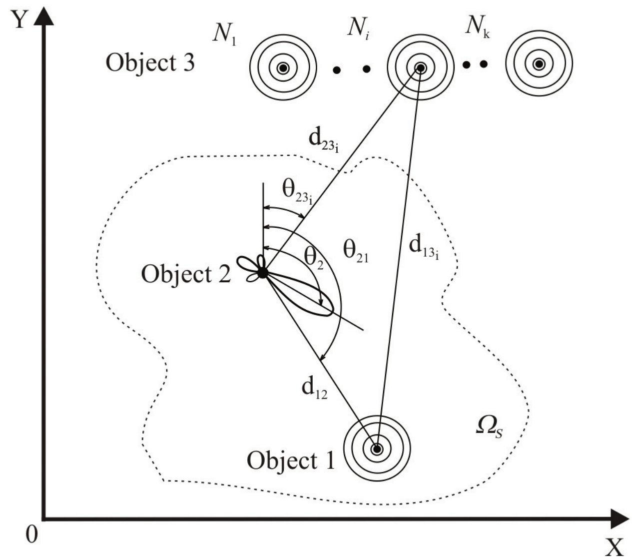


Fig. 9 Using a beam antenna system of receiver to protect against interference [2]

The interference immunity communication zone in the azimuthal plane was defined in [2, 15] as

$$\Omega_s = \left\{\forall\left(x, y\right) \in \Omega \mid K_{\sup}\left(x, y, \theta_2^*\right) \le K_{\text{th}}\right\} \tag{12}$$

where $K_{\sup} = P_N - P_S$ – the power suppression ratio [dB] of the useful signal P_S by the total radio interference P_N at the input of the radio receiver located at the point with coordinates $(x,\ y)$,

$K_{\text{th}} = \dfrac{1}{SNR_{\min}}$ – the threshold value of suppression ratio [dBm],

θ_2^* – the azimuth of receiver antenna RP of object 2 providing the minimum value $K_{\sup}$.

It was assumed that the radiation of radio interference sources is omnidirectional, all mobile radio communication means and radio interference sources are simultaneously within electromagnetic availability relative to each other. This situation is typical for urban conditions. However, in tactical calculations, the distances between model objects can increase up to several kilometers, which makes it possible for the radio channel to lose its operability, as well as for the radio exchange means to go beyond the zone of influence of the radio interference system. This takes the model used in [2, 15] out of the scope of its adequacy and leads to the need to take into account the range of radio means of the radio communication channel.

For such cases, the useful signal power P_S and the total radio interference power P_N at the input of the radio receiver should be calculated in accordance with the general Friis Eq. (1). The useful signal power levels P_{12} and P_{21} for objects receivers 1 and 2 are obtained from Eq. (7) and Eq. (10), respectively.

The total power of radio interference at the input of the radio receiver of object 1 is

$$P_{N_1} = 20\log\sum_{i=1}^{K}\frac{P_{3_i}\lambda^2}{\left(4\pi d_{13_i}\right)^2}, \text{ [dBm]} \tag{13}$$

where P_{3_i} – the power of the i-th source of radio interference,

d_{13_i} – the distance from object 1 to i-th source of radio interference.

The total power of radio interference at the input of the radio receiver of object 2 is

$$P_{N_2} = 20\log\sum_{i=1}^{K}\frac{P_{3_i}G_2\left(\theta_{23_i}-\theta_2^*\right)\lambda^2}{\left(4\pi d_{23_i}\right)^2}, \text{ [dBm]} \tag{14}$$

where d_{23_i} – the distance from object 2 to i-th source of radio interference;

θ_{23_i} – the azimuth of the radio receiver antenna of object 2 on i-th source of radio interference.

Taking into account the operability conditions of the mobile radio communication channel Eq. (8) and Eq. (9), the definition of the interference immunity communication zone should be written in the following form:

$$\Omega_s = \left\{\forall\left(x_1, y_1\right)\in \Omega_{E_2}, \forall\left(x_2, y_2\right)\in \Omega_{E_1} \left| \begin{array}{l} P_{N_1}\left(x_1, y_1\right) - P_{21}\left(x_1, y_1\right) \le K_{th} \\ P_{N_2}\left(x_2, y_2\right) - P_{12}\left(x_2, y_2\right) \le K_{th} \end{array} \right.\right\} \tag{15}$$

Fig. 10 shows the result of the modified algorithm [2] for calculating the bounds of the stable radio receive zone in the UHF/VHF band for mobile radio communication means under the action of two sources of radio interference, taking into account relationship Eq. (15).

Object 1 has a transmitter with a power of 1 W, the transmitter of object 2 has a power of 5 W. the sensitivity of radio receivers $E_{s1} = E_{s2}$=-0.25 μV.

The problem contains two sources of radio interference (objects 3) with a power of 1 W. The transmitter power of object 1 ensures the receiving of the radio signal by object 2 in the zone (8), indicated in the figure as Ω_{E1}. This zone is an outer circle with a radius of 3.6 km, its area is 19 % of Ω. Placement of object 2 outside the EMA zone of object 1 is impractical, since the radio communication channel in this case is inoperable.

The zone of stable radio exchange Ω_s calculated using definition Eq. (15) is filled with yellow color, has an irregular shape, close to a circle with a maximum radius of 2.9 km. The area of the stable radio receiving zone is 11 % of Ω.

Fig. 10 also shows three possible situations in which the radio channel may be, depending on the options for the location of object 2 with an antenna directed at object 1. The antenna of object 1 in all options is directed at object 2.

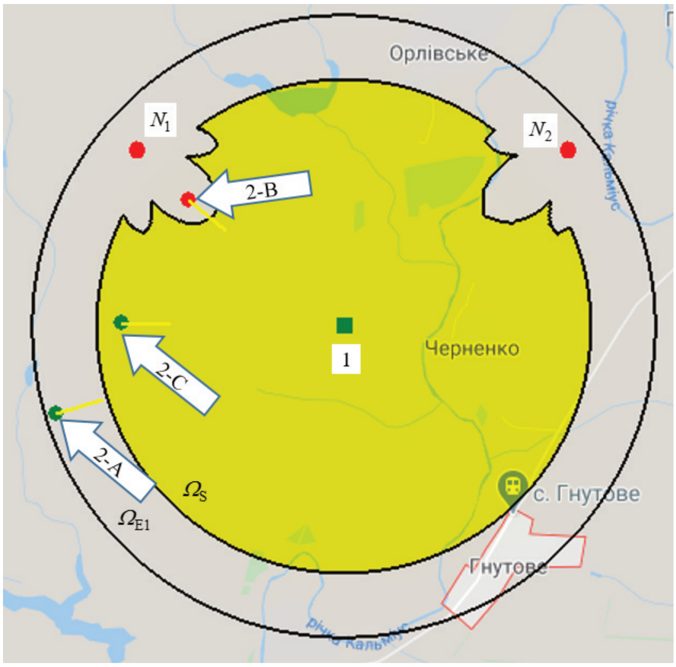


Fig. 10 Zone of stable radio receipt/ receiving in the UHF/VHF range for mobile radio communication aids in the conditions of the action of two sources of radio interference

In the first variant, when the object 2 is placed at the point 2-A, which is outside the zone of stable radio exchange Ω_s, the receiver of the object 2 receives the useful radio signal of the object 1 with a sufficiently low level of radio interference, i.e. condition $P_{N_2} - P_{12} \leq K_{th}$ is satisfied for it. At the same time, the condition $P_{N_1} - P_{21} \leq K_{th}$ is not satisfied for the receiver of object 1, the useful radio signal of the transmitter of object 2 is suppressed. Thus, in this embodiment, the radio communication channel is operational, but the radio exchange is partially suppressed.

In the second variant, when object 2 is placed at the point 2-B, which is outside the zone of stable radio exchange Ω_s, the conditions $P_{N_2} - P_{12} \leq K_{th}$ and $P_{N_1} - P_{21} \leq K_{th}$ are not satisfied. The radio exchange of mobile means is completely suppressed.

In the third variant, when object 2 is placed at the point 2-C, which is located within the zone of stable radio exchange Ω_s, conditions $P_{N_2} - P_{12} \leq K_{th}$ and $P_{N_1} - P_{21} \leq K_{th}$ are met for the receivers of both objects 1 and 2. Mobile radio communication means carry out a full-fledged radio exchange under the influence of a radio interference system. This situation persists for all points on the map $(x, y) \in \Omega_s$.

Thus, the use of relation Eq. (15) to determine the zone of interference-immune communication under the conditions of radio interference sources allows to take into account the scale of the terrain map, the range of the radio means of the radio channel and the range of radio interference sources. The conditions for the propagation of a useful radio signal and a radio interference signal are also taken into account. This makes it possible to apply the method [15] for tactical calculations.

6 Conclusions

Based on the well-known mathematical models of radio signal propagation, mathematical relationships are obtained to determine whether points of a topographic terrain map with a tactical situation belong to the EMA zone of radio emission sources as part of a mobile radio communication channel.

A practical method for bounds calculation of electromagnetic availability zone of radio means of a radio communication channel is proposed. It is based on a modified wave algorithm. The proposed modification of the wave algorithm consists in changing the rule for deciding whether the current point of the discrete working field belongs to the EMA zone of the radio emission source on the topographic terrain map with a tactical situation. This takes into account the receiver sensitivity, the transmitter power and the shape of the digitized RP of its antenna, the map scale, and the losses of signal power depending on the characteristics of the terrain. The already known techniques for modeling the propagation of a radio signal are easily integrated into the proposed algorithm.

The method is characterized by simplicity, high speed and reliability of calculations. Thus, according to the results of the studies, the duration of the calculation of the EMA zone of radio emission sources on a topographic terrain map with a tactical situation is on average 0.8..1.5 seconds.

The practical calculations were carried out for the Friis and Egli signal propagation models. The calculation results show that with a decrease in the frequency of the radio signal both in the VHF and UHF bands, the size of the EMA zone increases by 1.7 times for the Friis model and by 1.3 times for the Egli model. It should be noted that as the frequency increases in the UHF range, the sizes of the EMA zone obtained by different models tend to converge.

The shape of the EMA zone is determined by the digitized radiation pattern of the transmitter antenna obtained using special software.

The size of the EMA zone depends on the power and frequency of the radio transmitter, the power losses along the signal propagation path, and the sensitivity of the radio signal receiver. Practical calculations show that with an increase in the sensitivity of the radio receiver by 0.05 μV, the area of the EMA zone increases by 1.5 times.

Practical examples show the expediency of calculating the EMA of radio means on a terrain map with a tactical situation in the tasks of assessing the operationality of a mobile radio communication channel, as well as its availability for an enemy radio reconnaissance receiver.

In tactical calculations, the distances between radio communications can increase to several kilometers, which might put the operability of the radio channel in risk. In addition, with an increase in distance, it becomes possible for radio exchange means to go beyond the coverage area of the enemy’s radio interference system, and the conditions for the availability of a radio channel for enemy radio reconnaissance means may also change. For such tasks, practical examples show the expediency of calculating the EMA zones of radio means on a terrain map with a tactical situation.

The method developed earlier by the authors for calculating the boundaries of the area of stable radio receiving for mobile radio communications in the UHF/VHF bands under the influence of radio interference sources did not take into account the range of the radio means of the radio channel and the propagation conditions of the radio signal.

The algorithm for calculating the EMA of radio means described in this article makes it possible to expand the area of adequacy of this method for tactical calculations.

Acknowledgement

The work presented in this paper has been supported by the Main Directorate of the National Guard of Ukraine (research project No. DR 0118U004670).

References

[1] KUPRIYANOV, A. I. *Electronic Warfare* (in Russian). Moscow: University Book, 2013. ISBN 978-5-9502-0501-9.

[2] IOHOV, O.Yu, V.G. MALIUK, S.A. HORIELYSHEV, K.N. TKACHENKO, and S.V. HERASIMOV. Development of a Method for Boundary Determination of the Noise-resistant Area of the UHF/VHF Band. *Advances in Military Technology*, 2020, **15**(2), pp. 231-246. DOI 10.3849/aimt.01376.

[3] VOLOBUEV, A.P., M.Yu. JAKOVLEV and O.V. FEDIN. Method of Mathematical Modelling of Electromagnetic Accessibility of a Promising Mobile Radio Communication System (in Ukrainian). *Weapons and Military Equipment*, 2015, **2**(6), pp. 28-32. ISSN 2414-0615.

[4] VOLOBUEV, A.P., O.Yu. KORKIN and I.Yu. VOLOBUIEVA. Geometrical Interpretation of Electromagnetic Availability for Separate Radio as Part of Future Mobile Tactical Radio System (in Ukrainian). *Collection of Scientific Works of the Military Academy (Odessa). Technical Sciences* [online], 2014, **2**(2), pp. 25-32 [viewed 2022-02-05]. Available from: http://nbuv.gov.ua/UJRN/zbnpva_2014_2_6

[5] KALYUZHNYY, N.M., S.A. GALKIN, K.N. KORZHUKOV and A.V. KHRYAPKIN. Results of Realization as Software Product of Method of Construction of Areas of Electromagnetic Availability of Facilities of Radiomonitoring (in Russian). *Science and Technology of the Air Force of Ukraine*, 2015, **2**(19), pp. 111-114. ISSN 2223-456X.

[6] *MOTOTRBO™ DP4000 Series Digital Two-way Portable Radios* [online]. [viewed 2021-12-03]. Available from: https://cutt.ly/AYp8rV4

[7] PARSONS, J.D. *The Mobile Radio Propagation Channel*. 2nd ed. Hoboken: Wiley, 2000. ISBN 0-471-98857-X.

[8] *Calculation of Free-Space Attenuation.* Recommendation ITU-R P.525-4 [online]. [viewed 2021-11-26]. Available from: https://www.itu.int/rec/R-REC-P.525-4-201908-I/en

[9] EGLI, J.J. Radio Propagation above 40MC over Irregular Terrain. In: *Proceedings of the IRE*. IEEE, 1957, **45**(10), pp. 1383-1391. DOI 10.1109/JRPROC.1957.278224.

[10] DELISLE, G.Y., J.-P. LEFEVRE, M. LECOURS and J.-Y. CHOUINARD. Propagation Loss Prediction: A Comparative Study with Application to the Mobile Radio Channel. *IEEE Transactions on Vehicular Technology*, **34**(2), 1985, pp. 86-96. DOI 10.1109/T-VT.1985.24041.

[11] HATA, M. Empirical Formula for Propagation Loss in Land Mobile Radio Services. *IEEE Transactions Vehicular Technology*, **29**(3), 1980, pp. 317-325. DOI 10.1109/T-VT.1980.23859.

[12] OKAMURA, T., E. OHMORI, T. KAWANO, K. FUKUDA. Field Strength and its Variability in VHF and UHF Land Mobile Radio Service. *International Review of Electrical Engineering,* 1968, **16**(9-10), pp. 825-873. DOI 10.1109/PROC.1968.6860.

[13] *3D Electromagnetic Field Simulator for RF and Wireless Design* [online]. [viewed 2021-12-10]. Available from: https://cutt.ly/HtJrTD7

[14] PLAKSIENKO, V.S., N.E. PLAKSIENKO and S.V. PLAKSIENKO. *Signal Receiving and Processing Devices* (in Russian). Moscow: Educational-Methodical Publishing Center "Educational Literature", 2004. ISBN 5-8367-0026-X.

[15] MALIUK, V.G., O.Yu. YOHOV and I.V. KUZMINICH. Method for Determining the Boundaries of a Stationary Radio Exchange Zone for Internal Troops in Radio Suppression (in Ukrainian). *Weapons Systems and Military Equipment*, 2014, **1**(37), p. 56-62. ISSN 1997-9568.