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COMPUTER SIMULATION OF THE WORKING CONDITIONS OF A MOBILE RADIO COMMUNICATION CHANNEL ON THE MAP OF THE AREA

Introduction

Clarification of the range of the UHF/VHF radio source is an important task when organizing the functioning of a mobile radio channel, especially when conducting local combat operations by tactical units. Such tasks according to [1, 2] include: analysis of the radio channel's operability conditions; reduction of the enemy's radio reconnaissance effectiveness; protection of the radio channel from the influence of radio interference systems.

A common element of all these tasks is the use of the concept of the electromagnetic availability zone (EMA) of a radio radiation source. The electromagnetic availability zone of a radio transmitter is understood as a set of points in space in which this transmitter provides the minimum required radio signal power at the input of the corresponding receiver, taking into account its sensitivity.

Analysis of recent research and publications, purpose of the study

Based on certain provisions of the theory of electromagnetic fields and the theory of tensor calculus, in the article [1, 2] a mathematical model of the EMA of a military radio communication system based on the representation of the object of modeling by a quasi-crystal is proposed. The results obtained by the authors are theoretical in nature and have not yet been applied practically in solving the problems of organizing the operation of mobile radio communication systems.

Traditional path loss models use fundamental laws of physics and regression models that can be supported by measurements. In general, these methods are low-cost and successful for environments with low complexity. Achieving high accuracy in complex environments (e.g., urban environments with many buildings and obstacles) is associated with increased computational complexity, as shown in Table 1 based on the results of [4, 5, 6, 7, 8, 9]

Table 1. Comparative table of some loss models on the radio signal propagation path

Parameter	Friis (FSPL)	Egli	Okumura–Hata	COST-231 Hata	Walfisch–Ikegami
Frequency range	Any	40–900 MHz	150–1500 MHz	1500–2000 MHz	800–2000 MHz
Distance	Any	1–50 km	1–20 km	1–20 km	0,02–5 km
Type of terrain	Free space	Open, slightly crossed	Urban, suburban, rural	Urban, suburban	Dense urban development
Taking terrain into account	No	Part	No	No	No
Taking into account development	No	No	Statistically	Statistically	In detail
Model type	Theoretical	Empirical	Empirical	Empirical	Semi-empirical
Typical fault	±15–20 dB	±10–15 dB	±6–10 dB	±6–10 dB	±4–8 dB
Approximate number of operations per point	10–20	20–40	40–80	50–100	100–300
Computational complexity	Very low	Low	Low	Low	Medium
Main area of application	Preliminary estimates	Tactical VHF/UHF communication	2G/3G cellular network planning	GSM/DCS/LTE lower bands	Urban development, microcells

According to the results of the comparison, the Friis and Egli models are a useful tool for a quick initial assessment of coverage areas in the VHF/UHF bands, especially in field conditions without access to digital terrain maps.

The Friis free space propagation model, also known as Free Space Path Loss, FSPL, is used for initial estimations, overhead lines and satellite communications. The power loss of the radio signal is estimated using the relation [9]:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2 , \quad (1)$$

where P_R – the power [W] received by the antenna at a distance d [m],

P_T – the signal transmitter power [W],

G_T, 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 (1) can be represented in the following form:

$$P_R = P_T - L_P , [dB], \quad (2)$$

where L_P – the radio signal power transmission losses, which in free space according to [5] are calculated

$$L_P = 32.44 + 20 \log F_{MHz} + 20 \log D_{km} , [dB] , \quad (3)$$

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 [4]. 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 (3), the radio signal power losses are defined here as follows

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

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

More complex models correspond to the conditions of urban development and suburbs: Okamura, Hata, etc. [4, 7, 8].

To build a simple and fast method for calculating the boundaries of the EMA zone of radio equipment of a tactical-level mobile radio channel, it is advisable to limit ourselves to the simplest calculation ratios of radio signal power losses (3) and (4). If necessary, depending on the characteristics of a specific area and factors that need to be taken into account, the formulas for taking into account radio signal power losses can be replaced by more complex ones. In this case, it is necessary to take into account the issue of the complexity of the algorithm, which affects the possibility of its use in field conditions.

The purpose of the study is to develop a fast and accurate method for calculating the boundaries of the EMA zone of radio radiation sources within a tactical mobile radio communication channel in the UHF/VHF range with reference to a topographic map of the area.

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

Let us consider the interaction of radio means of a mobile radio channel taking into account the range of radio radiation sources.

Let us denote the area of a topographic map of the area with the operational situation plotted by Ω. In the general case, the model of a mobile radio channel contains the following objects (Fig. 1).

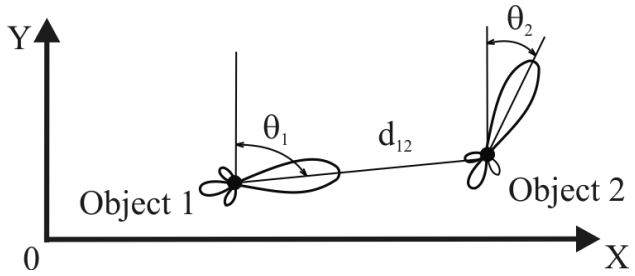
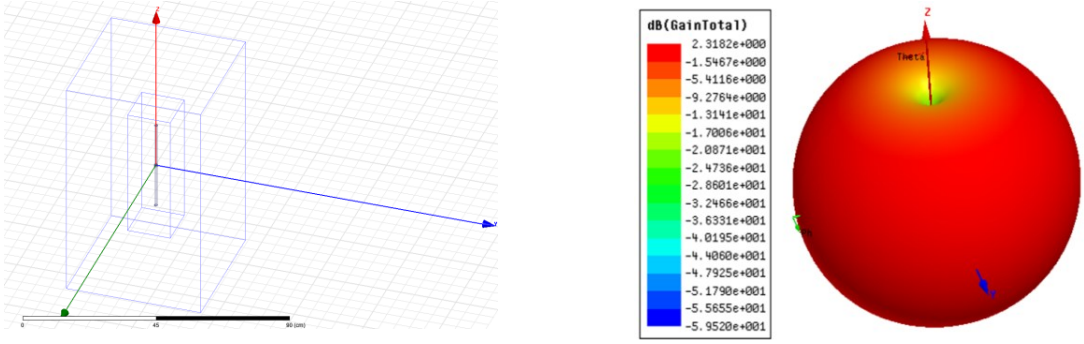


Figure 1. Mobile radio communication channel objects

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. 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 $E_s, [\mu V]$. 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 [11] Fig. 2 shows an example of calculating a dipole antenna.

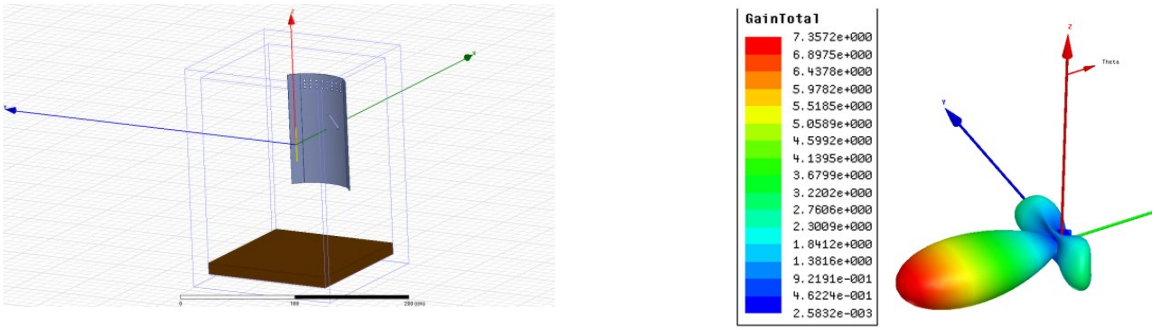


a) b)

Figure 2. Calculation of the directive diagram for dipole antenna
a) image of a dipole antenna model placed in a box b) pattern shape of nonresonant antenna arrangement

To protect the receiver from radio interference, any directional antenna or design with a protective screen that determines the appropriate radiation pattern can be used. Fig. 3 shows an example of calculating the radiation pattern of a beam antenna circuit consisting of a dipole antenna and a metal protective screen.

Let us consider the definition of the boundary of the EMA zone of the transmitter of object 1 during its interaction with the receiver of object 2.



a) b)

Figure 3. Calculation of the directive diagram for a dipole antenna equipped with a screen
a) image of a dipole antenna model and a screen placed in a box; b) directive diagram form of a beam antenna arrangement

For mobile radio means, when a matched antenna is directly connected to the receiver input with sensitivity and matched active input impedance, the minimum required power of the useful signal at the receiver input is determined by the corresponding ratio [11]:

$$P_{min} = \frac{E_s^2}{4R_A}. \quad (5)$$

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 [20], in MTP3000 radio stations the receiver sensitivity is 0.25 μV. 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 obviously 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 (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 DP of antennas:

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

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

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

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

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

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

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

where

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

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:

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

From the obtained relations (7) – (10) 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.

The boundary of the EMA zone (8) of the transmitter of object 1 for the receiver of object 2 correspond to the isoline of the level P_{min}, that is, the locus of points with coordinates (x_2, y_2), which are located at a height P_{min} and have other points with a different height in any of their neighborhoods:

$$I_{E_1} = \left\{ \begin{array}{l} \forall (x_2, y_2) \in \Omega \mid P_{12}(x_2, y_2) = P_{min}, \\ \forall \varepsilon > 0 : \exists (x', y') : |(x', y'), (x_2, y_2)| < \varepsilon, P_{12}(x_2, y_2) \neq P_{min} \end{array} \right\}. \quad (12)$$

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

Analysis of resources for computer visualization of contour lines within the framework of problem (12) allows us to draw the following [2]:

• the modern principle of interactivity, which imposes serious restrictions on the execution time of the program, makes the procedure of a complete search of map points unacceptable;

• well-known algorithms used in various application software packages (MatLab, Mathcad, Beta-Soft, etc.) cannot be used in other software systems, since their implementation procedures are absent, and it is impossible to scale the visualization area in proportions corresponding to real ones;

• the most popular algorithm for visualization of a two-dimensional scalar field is the Marching Squares algorithm [20]. The advantages of the method are its universality. The disadvantages of this method include the need to calculate the field values at all nodes of the initial regular grid, the presence of ambiguous cases when classifying contour fragments and ensuring contour isolation.

To calculate the coordinates of the isoline points (12), a next modification of the wave algorithm used in the works [9, 11, 12 , 13, 14] is used.

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 algorithm (Fig. 4) consists of three stages: initialization, wave propagation and formation of an array of zone border coordinates.

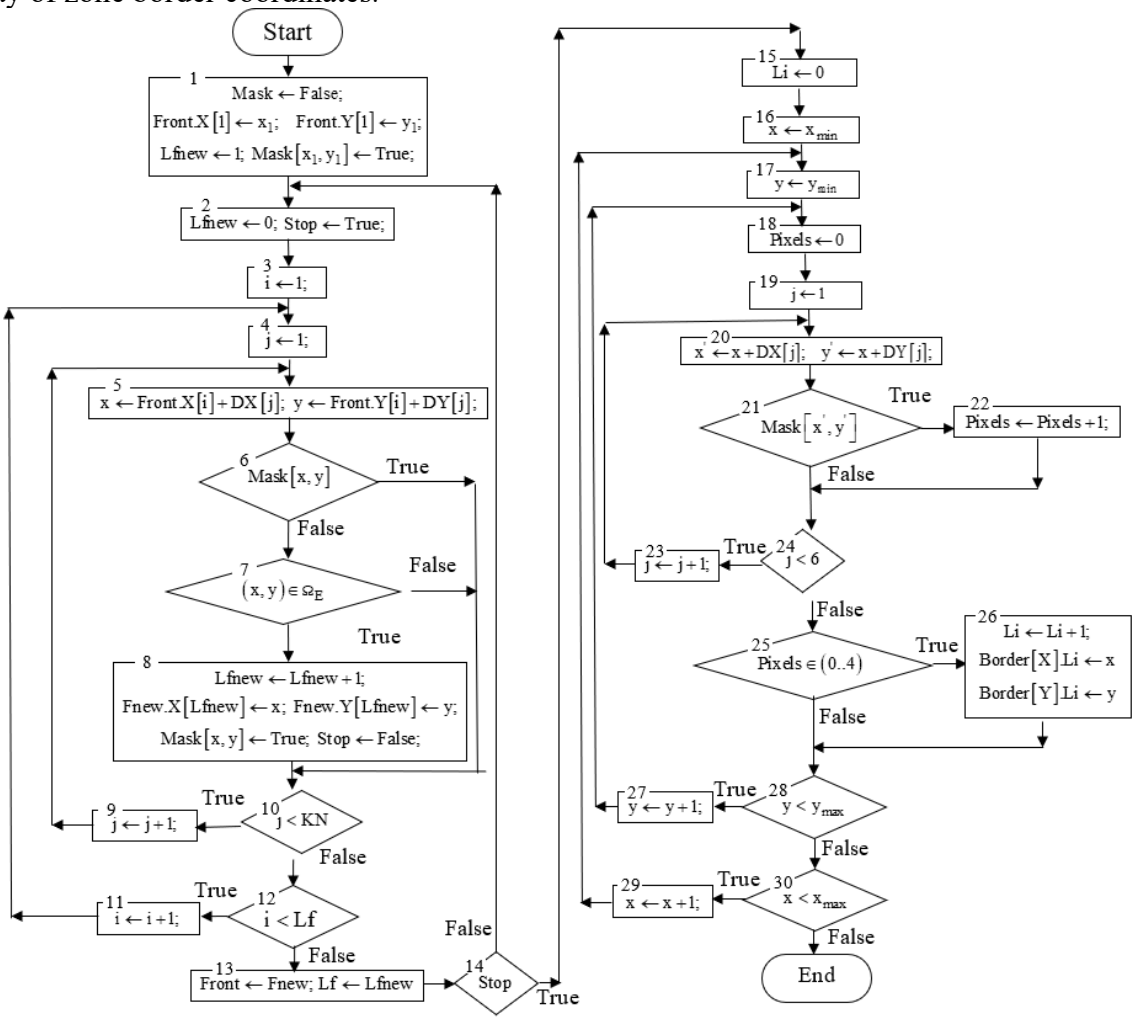


Figure 4. Algorithm for calculating the bounds of the electromagnetic availability zone of a radio emission source

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. At the beginning of the work, the process completion flag Stop = True is set. Then, all points of the current wave front Front are sequentially viewed. For each point of the front, it is possible to check the neighboring cells using a four-connected lattice (von Neumann neighborhood, Fig. 5a [18]) or an eight-connected lattice (Moore neighborhood, Fig. 5b[19]).

For the case of a 4-connected lattice, the working arrays DX = (0, 1, 0, -1) and DY = (-1, 0, 1, 0) are used. Thus, the points from above, right, bottom, left are checked. The parameter of the number of points for checking KN=4 (Fig. 5, block 10). For the case of an 8-connected lattice, the working

arrays DX = (-1, -1, 0, +1, +1, +1, 0, -1) and DY = (0, +1, +1, +1, 0, -1, -1, -1), the number of points for checking KN=8.

If a candidate point with coordinates (x, y) is free (block 6) and the condition (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 (8) ceases to be satisfied for any candidate points. In this case, the Stop flag switches to the next stage of the algorithm.

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 (8) and stored in the Border array – array of coordinates of the zone boundary points (blocks 25 and 26).

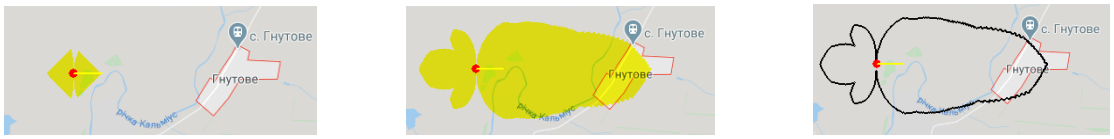
By counting the number of cells of the bit mask with the True state and referring to the map scale, it is possible to additionally estimate the area of the obtained EMA zone.



a) von Neumann scheme b) Moore's scheme

Figure 5. Options for checking points of the current wavefront

Fig. 6 shows the main stages of the algorithm (Fig. 4), obtained by the authors in the task of calculating the boundary of the EMA zone of the transmitter on the map of the area.



a) b) c)

Figure 6. Stages of the algorithm for calculating the bounds of the EMA zone of a radio emission source

Fig. 6a 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. 6b. Here the Stop flag is set to True. The stage of laying the boundaries of the EMA zone is illustrated in Fig. 6c.

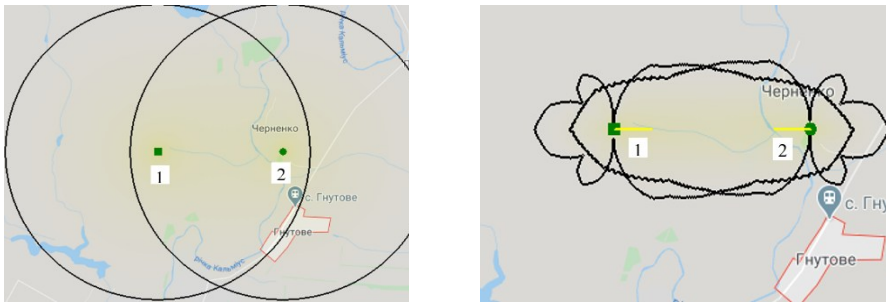
The scale of the map taken from Google Maps is 19 m/pixel. The calculations were made for a transmitter with a power of 1 W operating at a frequency of 446 MHz and for a receiver sensitivity of 0.25 μV.

The maximum distance from the transmitter location point to the EMA boundary points corresponds to the main lobe of the antenna DP 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 of the transmitter. So, in the example above, the area of the zone is equal to 5.56 km^2, which is 3 % of the total area of the topographic terrain map with a tactical situation.

The method of verification of the obtained calculation results with experimental measurements is given in [5].

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 (11). The Fig. 7 shows two options for calculating adjacent EMA zones of an operable radio channel for omnidirectional (Fig. 7a) and directional antenna (Fig. 7b) systems.



a) b)

Figure 7. Examples of calculation of EMA zones of mobile radio communications means source

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 (11) are satisfied for both options.

The complexity of the proposed algorithm is linear, $O(n)$, and its complexity is reduced compared to the Marching Squares algorithm, because the analysis of the condition of the point belonging to the EMA zone (8) is not performed at all points of the map, but only at the points of wave propagation. The stage of forming the array of coordinates of isoline points on the map, on which the scan of the bit mask of the map is performed, does not require complex calculations, therefore it is performed quickly.

The influence of the rule of polling neighboring cells for each front point (4-connected or 8-connected lattice) on the complexity of the algorithm can be illustrated by the example of calculating the EMA zone of radio device 1, located on the left in Fig. 7a. During the calculation, the following parameters were recorded: KolOpros – the total number of points checked, KolCalc – the total number of free points for which the signal power calculation operation was performed (block 7), Countpix – the total number of points for which the signal power calculation led to their inclusion in the EMA zone (block 8), Max step number – the total number of wave propagation steps, time – the total time for calculating the EMA zone, ms.

The values of these parameters for both types of neighborhood are given in Table 2.

Table 2. Complexity parameters for two types of neighborhood

Polling rule	KolOpros	KolCalc	Countpix	Max step number	time, ms
4x (Von Neumann scheme)	478804	121264	119701	277	922
8x (Moore's scheme)	957608	123457	119701	196	860

Since in the von Neumann scheme for each front point 4 neighboring cells are checked instead of eight, it is much better than the 8-connected lattice (the KolOpros parameter is significantly smaller). The KolCalc parameter in the Moore scheme also differs in a larger direction due to the diagonal points. Thus, from the point of view of the number of check operations per step, the 4-

connected lattice is better than the 8-connected one. But on the other hand, the use of different methods of polling neighboring cells for each front point leads to a different number of wave propagation steps (Fig. 8).

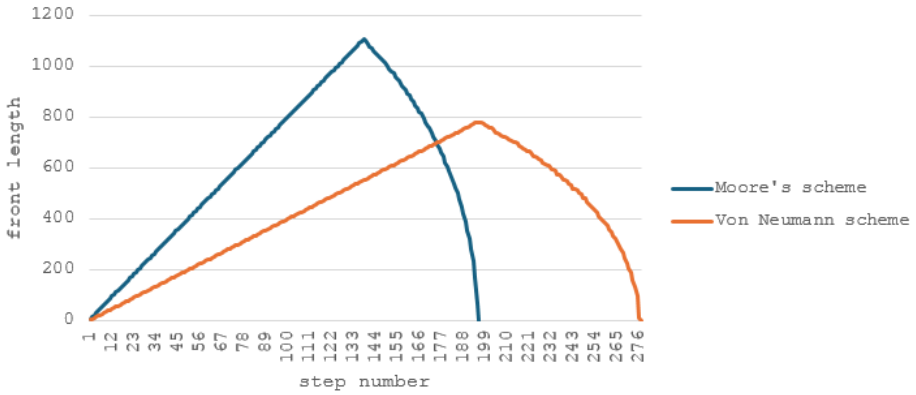


Figure 8. Dependence of the front length on the step number

For the von Neumann scheme, the total number of wave propagation steps (Max step number) is 277, and for the Moore scheme – 196. This explains the overall gain in time (parameter time) due to the smaller number of front array update operations (block 13). This makes the 4-connected von Neumann scheme more economical for small maps. For large maps, it is better to use the 8-connected Moore scheme.

To assess the influence of the parameters of the radio means of the communication channel on the dimensions of the EMA zone, practical calculations were carried out for the Friis and Egli signal propagation models. Fig. 9 shows the dependence of the area of this zone of the MTP3000 radio station[20] equipped with an isotropic antenna on the signal power in the range from 1 to 5 W.

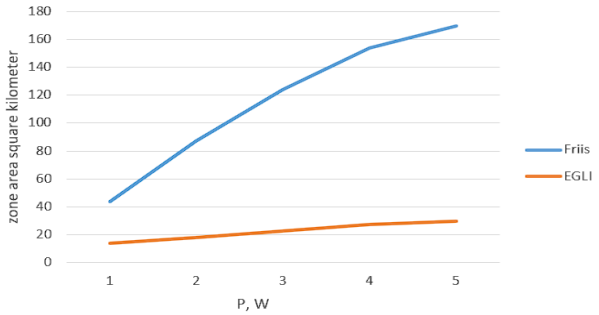
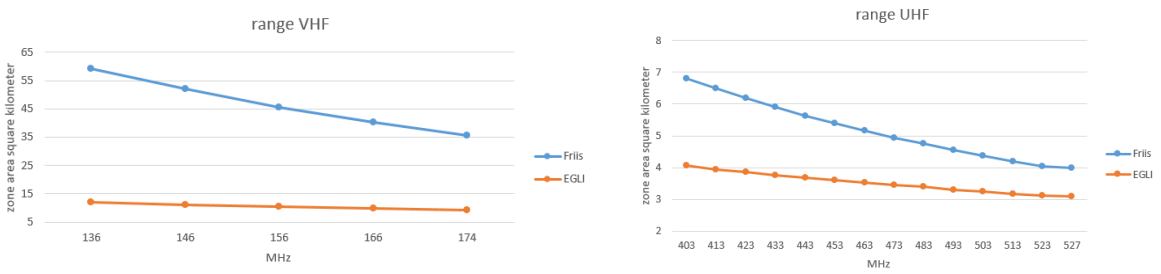


Figure 9. Dependence of the size of the EMA zone of a radio radiation source on the signal power

Fig. 10 shows the dependence of the area of the EMA zone of the MTP3000 radio station on the signal frequency in the VHF (136-174 MHz) and UHF (403-527 MHz) bands.



a) b)

Figure 10. Dependence of the size of the EMA zone on the signal frequency

The results of the calculations show that with a decrease in the radio signal frequency in both the VHF and UHF ranges, 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 with an increase in the frequency in the UHF range, the sizes of the EMA zone obtained by different models tend to converge.

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

Therefore, the size of the EMA zone depends on the power and frequency of the radio transmitter, power losses in the signal propagation path and the sensitivity of the radio receiver. The shape of the EMA zone is determined by the digitized directional pattern of the transmitter antenna.

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 directional diagram of 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.

The results of the studies carried out make it possible to evaluate the fulfillment of the conditions for the operability of a mobile radio communication channel, which depend on the transmitter power, the orientation of the antenna pattern, power losses along the signal propagation path, and the sensitivity of the receiver.

The practical results obtained can be used by Ukrainian security forces during crisis situations to ensure reliable transmission of operational information during conduct of operations of troops (forces), in scientific research works in the design of new systems for protecting radio networks, in the educational process for training officers in managing radio communication units

Possible directions for continuing research within the framework of the proposed concept of assessing the operability of a VHF/UHF radio channel are to clarify the factors that relate to the characteristics of radio signal propagation in the area and affect the shape and size of the EMA zone of radio radiation sources: atmospheric conditions, terrain, reflection and refraction of waves, etc.

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