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ANTENNA ARRAY AS A CONSTRUCTIVE ELEMENT OF INCREASING CYBER-SECURITY OF NETWORK SATELLITE SYSTEM RECEIVERS

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Abstract

Purpose: *to adapt the techniques of constructive synthesis of phased antenna arrays. On the basis of the received technique, to optimize the antenna array of receiving devices of consumer equipment for the adaptive antenna system of network satellite systems.* ***Methods:*** *the approach is based on the methods for synthesis of phased antenna arrays and antennas with a continuous opening.* ***Results:*** *in the article we have suggested a method for the constructive synthesis and optimization of the antenna array of adaptive systems of interference compensation for receiving devices of global navigation satellite systems on the basis of the methods for the synthesis of phased antenna arrays PAR in the form of a directional pattern. The method of synthesizing the antenna array is confirmed by the modeling results.* ***Discussion:*** *the method is proposed for designing the optimal antenna array in the adaptive antenna system of the receiving devices of consumer equipment of the network satellite systems, for protection from cyber threats - ensuring accessibility and integrity of navigational data.*

Keywords: adaptive antenna system; antenna array; constructive synthesis; navigation data availability; network satellite systems; optimization; radiation pattern.

1. Introduction

Network satellite systems (NSS) provide high-precision navigation on a global scale and are able to solve the problems of navigational support of any mobile objects.

One of the NSS segments are global navigation satellite systems (GNSS) such as GPS, GLONASS, GALILEO. These GNSS provide coordinate-time support, which is the basis for the efficient operation of many branches of the economy and is an important part of modern transport systems, digital telecommunications systems, command and control systems as well as precision weapons.

However, while operating GNSS receiver devices of consumer equipment, the facts of their exposure to cyber threats - jamming and spoofing - were revealed. This affects the availability and integrity of navigation data [1-4] (See Fig. 1).

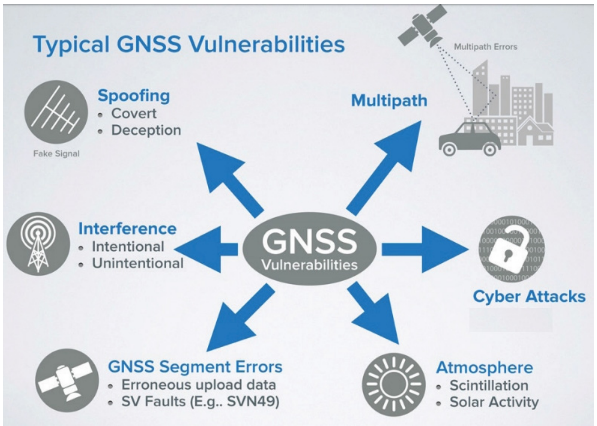


Fig. 1. Typical GNSS vulnerabilities

Thus, the vulnerability of GNSS in cyber threats is now a universally recognized fact. This vulnerability applies equally to all GNSS because the principles of their construction and frequency ranges are quite close.

Currently, an effective solution in protecting against cyberthreats violating the integrity and availability of navigational data, i.e. increasing their noise immunity, is the introduction of spatial filtering methods based on adaptive antenna systems (AAS) in GNSS receiver devices of consumer equipment that form the "zero" antenna pattern in the direction of the source of interference [5-7]. One of the constructive elements that solve this problem is the AAS antenna array (AA), which serves as both a source of information for spatial filtering and the object of control [5-7].

2. Analysis of the research and publications

The history of the AA has been around for many years, the last two decades have become a time of full development of the possibilities for both the use of antenna arrays and their calculation. The main application of AA is in radiolocation and communication systems, where phased AAs (PAAs) are actively implemented. Methods for the constructive calculation of single AA elements and complete synthesis of PAAs have been adequately covered in the references section from which papers [8-10] can be cited. However, the functional requirements that are imposed on the PAA and to the AAS differ in the way in which the antenna pattern is formed [11]: the width of the main lobe in the vertical plane is 180 °, the width of the main lobe in the horizontal plane is 360 °, the absence of side lobes, absence of radiation in the backward hemisphere (See Fig. 2).

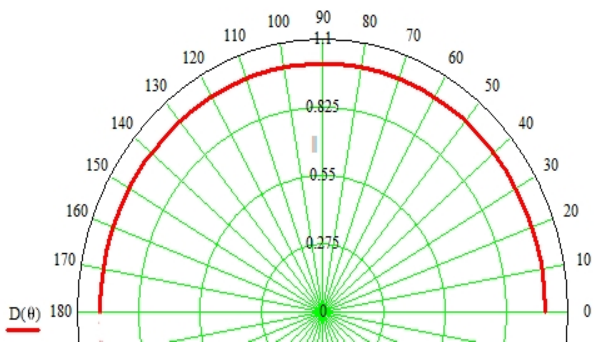


Fig. 2. The ideal antenna pattern of the GNSS receiver

Unfortunately, up to the present time, the issues on constructive synthesis of AAS AA receiving devices of GNSS consumer equipment have not been considered in publications.

3. Research task

The task of the research is to carry out a constructive synthesis and optimization of the AAS AA of receiving devices of the GNSS consumer equipment on the basis of the methods of constructive synthesis of PAA AA.

4. Results and Discussion

As the constructive parameters of a flat AA we can consider (See Fig. 2): parameters of the direction diagram, lattice distance d_x, d_y – distance between AA emitters (lattice distance), correlation d/λ – lattice distance to wave length, AA aperture – l_1, l_2, x_n, y_n – AA emitters coordinates, N – number of elements in AA.

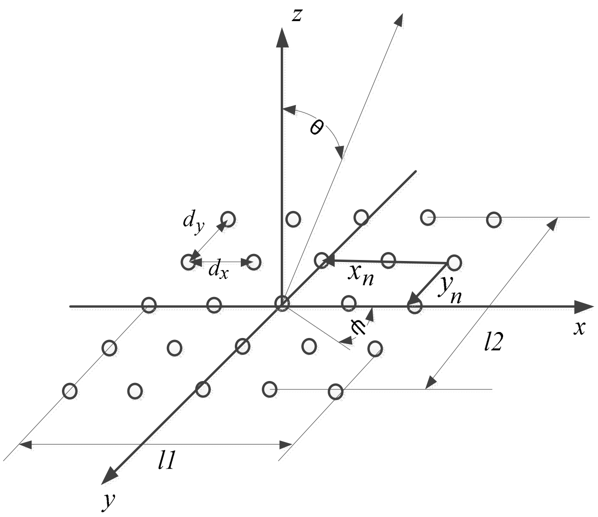


Fig. 3. AAS antenna array

We shall not pay any attention to the constructive synthesis of AA single element (emitter), while our main aim will be to determine the lattice distance of array, or correlation d/λ, which defines location of AA emitter and is the main one for creation of RP with the following parameters: the width of the main lobe in the vertical plane - 164 °, the width of the main lobe in the horizontal plane - 360 °, has a minimum level $P_{\text{бпл}}$ (dB), or the absence of lateral lobes, the minimum level of back radiation $P_{зд}$ (dB) [11].

One of the methods of optimizing AA is to obtain constructive antenna parameters according to a given form of the AA radiation pattern [8,10] using the Fourier integral. As calculated values of N are the complex amplitudes of excitation currents {Fn} of the antenna radiators and the coordinates N of the lattice elements, the coordinates of the radiators are the points in which the argument of the excitation currents {Fn} makes jumps, that is, changes the phase.

Let us conduct a synthesis of AA, which has a radiation pattern described with the equation $D(\theta)=\sqrt{\sin^2(\theta)+\cos^2(\theta)}$ (See Fig. 2) in the planes *X*0*Z* and *Y*0*Z*.

Emitters are arranged on a plane and form an orthogonal lattice (See Fig. 3). The number of emitters located in one line is N1, and the number of emitters in one column is N2. There will be N = N1N2 elements in the lattice.

Let us consider that $d_y=d_x=d$, AA is square.

We shall analyze not the radiation pattern but an array's multiplyer.

$$D(\theta,\varphi)=D_x(\theta,\varphi)D_y(\theta,\varphi),$$

where

$$D_x(\theta,\varphi)=\sum_{n=1}^{N}F_n e^{j(n-1)2\pi\left(\frac{d_x}{\lambda}\right)\sin\theta\cos\varphi}, \qquad (1)$$

$$D_y(\theta,\varphi)=\sum_{k=1}^{N}F_n e^{j(k-1)2\pi\left(\frac{d_y}{\lambda}\right)\sin\theta\sin\varphi}.$$

Let us convert the equation (1). Then we shall position the coordinate system in such a way, so that the abscissas of the two extremes of the system are equal to *-l₁/2* and *l₁/2*, while the ordinates of the two extreme points are equal to *-l₂/2* and *l₂/2* (See Fig. 3).

Let us choose the scale for the emitters of the system so that the they are located in a square with sides equal to 2π. We will use for that the following:

$$\frac{2\pi}{l_1}x_n=\mu_n,\quad \frac{2\pi}{l_2}y_m=\nu_m.$$

Apart from the we will note

$$z_1=\frac{l_1}{\lambda}\sin\theta\cos\varphi,\quad z_2=\frac{l_2}{\lambda}\sin\theta\sin\varphi,$$

$$D(\theta,\varphi)=R(z_1z_2).$$

The function *R(z₁,z₂)* will have an AA radiation pattern described by the equation [10]

$$R(z_1z_2)=\sqrt{\left[1-\left(\frac{\lambda z_1}{l_1}\right)\right]^2\left[1-\left(\frac{\lambda z_2}{l_2}\right)\right]^2}.$$

Then the RP will look like

$$R(z_1,z_2)=\sum_{p=-n}^{n}\sum_{q=-m}^{m}F_{p,q}\exp[j(\mu_n z_1+\nu_m z_2)]. \qquad (2)$$

Let us introduce the notation (the transition from polar coordinates to rectangular)

$$u_1=2\pi\left(\frac{d_x}{\lambda}\right)\sin\theta\cos\varphi,\ u_2=2\pi\left(\frac{d_y}{\lambda}\right)\sin\theta\sin\varphi.$$

At the same time $\mu_p z_1=pu_1$ and $\nu_p z_2=qu_2$. So,

$$R(u_1,u_{u2})=\sum_{p=-n}^{n}\sum_{q=-m}^{m}F_{p,q}\exp[j(pu_1+qu_2)]. \qquad (3)$$

We will look for a solution in the form (par. 4.4 [10])

$$F_{p,q}=\sum_{k=0}^{2n}\sum_{l=0}^{2m}A_{k,l}\exp\left[-j\left(k\frac{2\pi}{N_1}+l\frac{2\pi}{N_2}\right)\right]. \qquad (4)$$

Having substituted (4) in (3), we get

$$R(u_1,u_2)=\sum_{k=0}^{2n}\sum_{l=0}^{2m}A_{k,l}\frac{\sin N_1\left(\frac{u_1}{2}-\frac{k\pi}{N_1}\right)}{-N_1\sin\left(\frac{u_1}{2}-\frac{k\pi}{N_1}\right)}\times$$
$$\times\frac{\sin N_2\left(\frac{u_2}{2}-\frac{k\pi}{N_2}\right)}{-N_2\sin\left(\frac{u_2}{2}-\frac{k\pi}{N_2}\right)}. \qquad (5)$$

Considering (4.13) [10] we get

$$F_{p,q}=\frac{1}{N}\sum_{k=0}^{2n}\sum_{l=0}^{2m}R\left(k\frac{2\pi}{N_1},l\frac{2\pi}{N_2}\right)\times$$
$$\times\exp\left[-j\left(k\frac{2\pi p}{N_1}-l\frac{2\pi q}{N_2}\right)\right]. \qquad (6)$$

Expression (6) completely determines the system of emitters to create a given radiation pattern, module (6) defines the values of currents $F_{p,q}$ in the emitters, while points where argument $F_{p,q}$ (6) makes jumps correspond to the coordinates of emitters location [10].

The solution of expression (6) can be obtained using the matrix form of the record (2) or (3).

In the matrix form, the expressions (2), (3) can be represented as follows

$$[\mathbf{E}]\left|\mathbf{F}\right\rangle = \left|\mathbf{R}\right\rangle. \qquad (7)$$

Matrix elements [**E**] of the system (7) are defined by the correlation

$$e_{n,k} = e^{j(n-1)2\pi\left(\frac{d_x}{\lambda}\right)\sin\theta\cos\varphi}\, e^{j(k-1)2\pi\left(\frac{d_y}{\lambda}\right)\sin\theta\sin\varphi}.$$

Elements of the vector-column **F** are unknown currents in the emitters of AA, and elements of the vector-column **R** are unknown currents in a given AA radiation pattern.

For a linear AA, the resulting solution of system (7) gives an approximate solution that is the best in terms of minimizing the mean square deviation of the synthesized RP. Since the rank of the matrix [**E**] is equal to N, the solution of the problem of amplitude-phase synthesis can be found in the form

$$\left|\mathbf{F}\right\rangle = [\mathbf{E}]^{+}\left|\mathbf{R}\right\rangle, \qquad (8)$$

where $[\mathbf{E}]^{+}$ is a pseudo-inverse matrix for the matrix [**E**].

For a flat AA with the size $N\times N$ $[\mathbf{E}]^{+}=\mathbf{E}^{-1}$.

For further calculations, we will calculate the maximum aperture of AA. Let us use the expression (4.29) [10]

$$l_{\max} \geq \frac{\max\left|D(\theta)\right|}{\left(\frac{\pi}{\lambda}\right)\cos\theta}. \qquad (9)$$

In this case θ is an angle, for which *D*(θ) accepts maximum value. The radiation pattern is normalized to 1, hence , max|*D*(θ)| =1, *θ* =0 °. Having substituted data in (9) we finally get $l_{max} \geq 0.318\lambda$.

Let us calculate the coordinates of the AA emitters, using the expression (6) for the range of L1 GPS, the results of calculation are reduced into table 1 (all calculations were made to obtain a radiation pattern without side lobes).

Table 1

Coordinates of AA emitters location

λ= 0,19042541036675934 м			
N	$l_1=l_2=l_{max}$ (AA aperture)	*d/λ* calculated	*d/λ* constructive implementation
2×2	*0.375λ*	0.25	0.25
2×2	*0.75λ*	0.5	0.25 ÷ 0.5
3×3	*0.75λ*	0.25	0.25
4×4	*0.75λ*	0.21	0.2 ÷ 0.25
5×5	*1.25λ*	0.2	0.2
6×6	*1.25λ*	0.2	0.2

The calculated radiation pattern module for AA 2 × 2 for parameters from the first row of tab. 1 is shown in Fig. 3

Fig. 4 shows that the radiation pattern of the synthesized AA corresponds to the requirements for antennas of the GPS system [10].

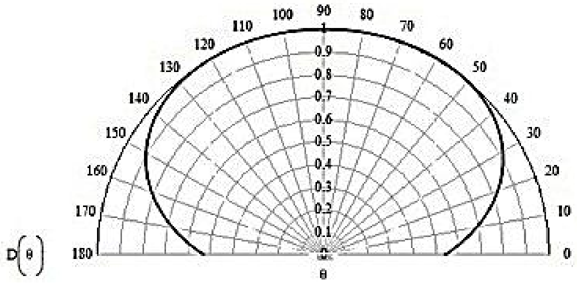
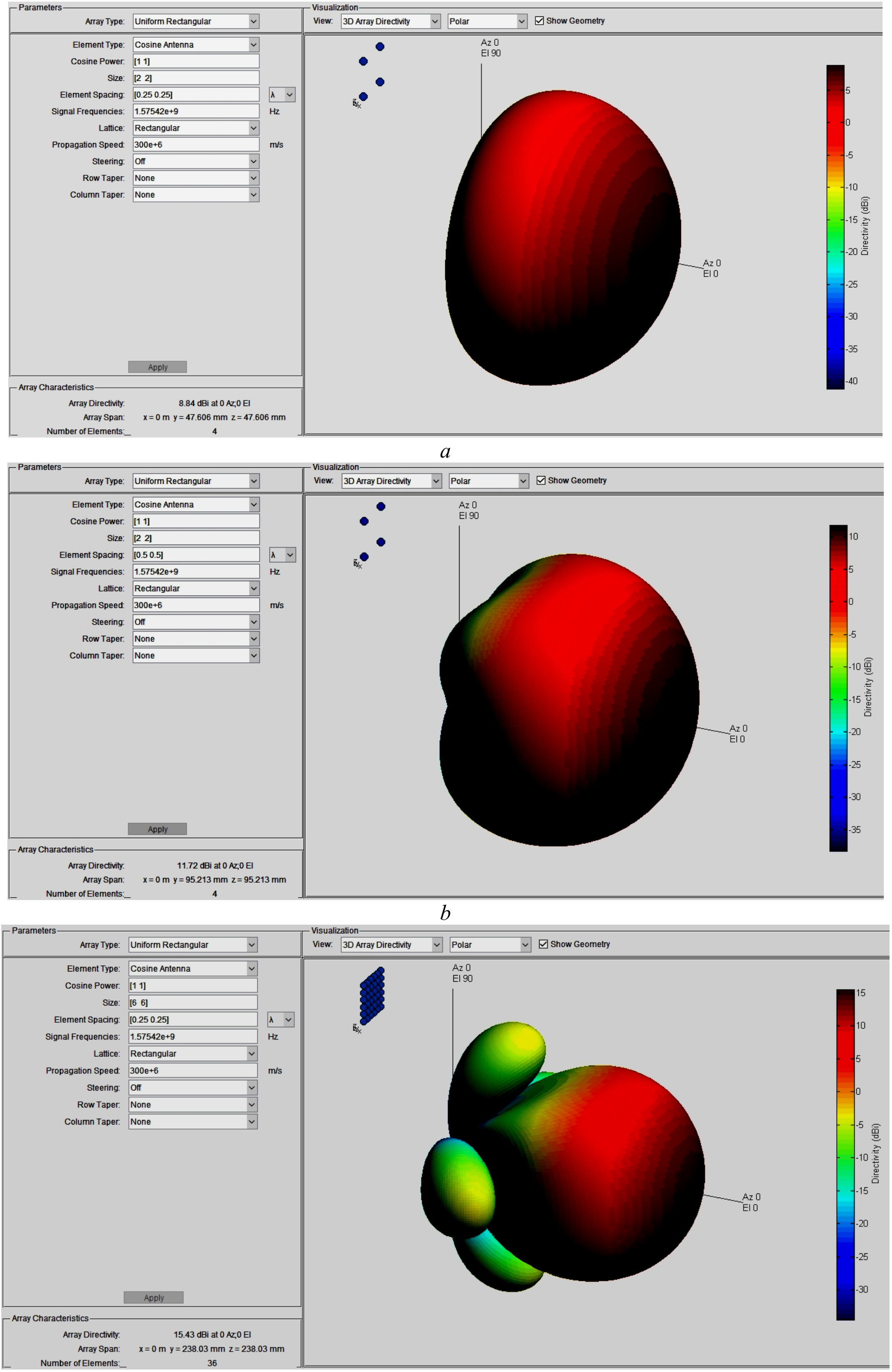


Fig. 4. Calculated radiation pattern for antenna array

According to the calculated coordinates of the emitters, the ratio *d/λ* (Table 1) will be carried out by the mathematical modeling of the flat AA RP.

Simulation condition is the complete absence of lateral lobes in the RP. The purpose of the simulation is to confirm the results of the AA synthesis. The simulation results are shown in Fig. 5.

You can use the parameter - P_{max}-$P_{бл}$ difference (where P_{max} is the maximum level of the main lobe, $P_{бл}$ is the maximum level of side lobes) of flat AA with the number of elements from 2×2 to 6×6 in order to select the AA step while designing. The graph of the P_{max}-$P_{бл}$ difference as a function of the step of AA is shown on Fig. 6. Using this graph, you can select the optimal step of AAS AA.



Parameters
Array Type: Uniform Rectangular
Element Type: Cosine Antenna
Cosine Power: [1 1]
Size: [2 2]
Element Spacing: [0.25 0.25] λ
Signal Frequencies: 1.57542e+9 Hz
Lattice: Rectangular
Propagation Speed: 300e+6 m/s
Steering: Off
Row Taper: None
Column Taper: None
Array Characteristics
Array Directivity: 8.84 dBi at 0 Az;0 El
Array Span: x = 0 m y = 47.606 mm z = 47.606 mm
Number of Elements: 4
Visualization
View: 3D Array Directivity Polar ☑ Show Geometry

a

Parameters
Array Type: Uniform Rectangular
Element Type: Cosine Antenna
Cosine Power: [1 1]
Size: [2 2]
Element Spacing: [0.5 0.5] λ
Signal Frequencies: 1.57542e+9 Hz
Lattice: Rectangular
Propagation Speed: 300e+6 m/s
Steering: Off
Row Taper: None
Column Taper: None
Array Characteristics
Array Directivity: 11.72 dBi at 0 Az;0 El
Array Span: x = 0 m y = 95.213 mm z = 95.213 mm
Number of Elements: 4
Visualization
View: 3D Array Directivity Polar ☑ Show Geometry

b

Parameters
Array Type: Uniform Rectangular
Element Type: Cosine Antenna
Cosine Power: [1 1]
Size: [6 6]
Element Spacing: [0.25 0.25] λ
Signal Frequencies: 1.57542e+9 Hz
Lattice: Rectangular
Propagation Speed: 300e+6 m/s
Steering: Off
Row Taper: None
Column Taper: None
Array Characteristics
Array Directivity: 15.43 dBi at 0 Az;0 El
Array Span: x = 0 m y = 238.03 mm z = 238.03 mm
Number of Elements: 36
Visualization
View: 3D Array Directivity Polar ☑ Show Geometry

c

Fig. 5. Calculated radiation patterns of 2×2 AA step 0.25λ a), 2×2 step 0.5λ b), 6×6 step 0.25λ c)

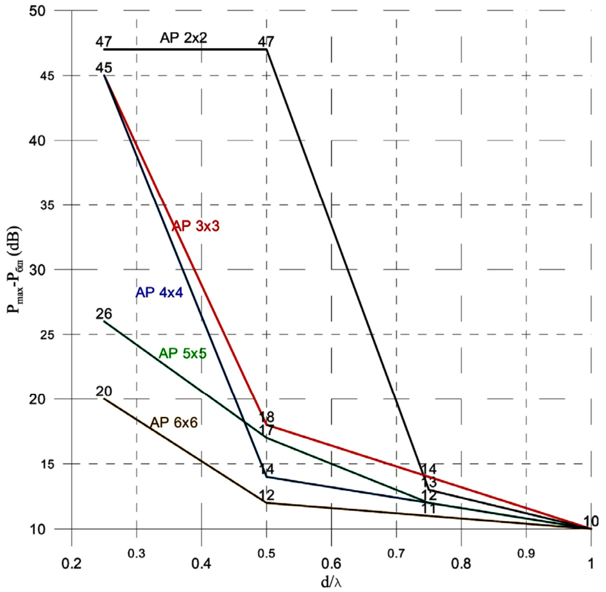


Fig. 6. Dependence of P_{max}-$P_{бл}$ on the ratio d/λ

Considering the results of the simulation, the following conclusions can be drawn:

- the optimal one can be considered the ratio d/λ, in which the P_{max}-$P_{бл}$ difference will be maximal and there will be a complete absence of lateral lobes in the AA radiation pattern;

- the optimal ratio d/λ can be considered a value from 0.2 to 0.25, under these conditions, the P_{max}-$P_{бл}$ difference has a maximum value, and radiation pattern has no lateral lobes.

5. Conclusions

To protect against cyber threats for NSS in the GNSS equipment, it is possible to use AAS, which can significantly reduce the signal reception ratio from the direction where the source of interference is located.

In this article we have suggested a method for optimizing the antenna array of adaptive interference compensation systems for receiving devices of global navigation satellite systems on the basis of the methods for the synthesis of PAA antenna arrays in the form of a radiation pattern. The results obtained are confirmed by modeling.

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Антенна решітка як конструктивний елемент підвищення кібербезпеки приймачів мережевих супутникових систем

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Мета: адаптувати методики конструктивного синтезу фазованих антенних решіток. На основі отриманих методик провести оптимізацію антенної решітки приймальних пристроїв апаратури споживачів адаптивної антенної системи мережевих супутникових систем. **Методи**: підхід базується на методах синтезу фазованих антенних решіток і антен з безперервним розкривом. **Результати**: у роботі на основі методик синтезу антенних решіток ФАР за формою діаграми спрямованості, запропонований метод конструктивного синтезу і оптимізації антеною решітки адаптивних систем компенсації перешкод для приймальних пристроїв глобальних навігаційних супутникових системи. Метод синтезу антеною решітки підтверджений результатами моделювання. **Обговорення**: в роботі на основі методик синтезу антенних решіток ФАР за формою діаграми спрямованості, запропонований метод конструктивного синтезу і оптимізації антенної решітки адаптивних систем компенсації перешкод для приймальних пристроїв глобальних навігаційних супутникових систем для захисту від кіберзагроз – забезпечення доступності та цілісності навігаційних даних. Метод синтезу антенної решітки підтверджений результатами моделювання.

Ключові слова: антенна решітка; адаптивна антенна система; діаграма спрямованості; доступність навігаційних даних; конструктивний синтез; мережеві супутникові системи; оптимізація.

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Антенная решетка как конструктивный элемент повышения кибербезопасности приемников сетевых спутниковых систем

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Цель: адаптировать методики конструктивного синтеза фазированных антенных решеток. На основе полученных методик провести оптимизацию антенной решетки приемных устройств аппаратуры потребителей адаптивной антенной системы сетевых спутниковых систем. **Методы:** подход базируется на методах синтеза фазированных антенных решеток и антенн с непрерывным раскрывом. **Результаты:** в работе на основе методик синтеза антенных решеток ФАР по форме диаграммы направленности, предложен метод конструктивного синтеза и оптимизации антенной решетки адаптивных систем компенсации помех для приемных устройств глобальных навигационных спутниковых системы. Метод синтеза антенной решетки подтвержден результатами моделирования. **Обсуждение:** в работе на основе методик синтеза антенных решеток ФАР по форме диаграммы направленности, предложен метод конструктивного синтеза и оптимизации антенной решетки адаптивных систем компенсации помех для приемных устройств глобальных навигационных спутниковых систем для защиты от киберугроз – обеспечения доступности и целостности навигационных данных. Метод синтеза антенной решетки подтвержден результатами моделирования.

Ключевые слова: антенная решетка; адаптивная антенная система; диаграмма направленности; доступность навигационных данных; конструктивный синтез; оптимизация; сетевые спутниковые системы.

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