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An Implementation of Interactive Application for the Synthesis of Communication Systems with Antenna Arrays

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Abstract

Introduction. Modern radar and communication systems incorporate phased array antennas. The synthesis of such systems involves the problem of formulating requirements for their constituent parts, modules and units. In order to solve this problem, it is essential to calculate the coverage area and to assess the impact of system components. The analysis and synthesis of such complex systems can be facilitated by applying interactive data visualization, which requires calculation of the necessary characteristics in a timely manner.

Aim. To develop an interactive software application for supporting the synthesis of communication systems incorporating antenna arrays and for improving operational characteristics of such systems.

Materials and methods. To accelerate the calculation of radiation patterns, an antenna array pattern in a form suitable for Fast Fourier Transform computations was used. To obtain the required amplitude-phase distributions, the Kotelnikov series expansion and a genetic algorithm were used.

Results. The developed software application is capable of displaying the amplitude-phase distribution, the directivity pattern of a linear equidistant array and the coverage area. It is possible to interactively change the amplitude-phase distribution at the radiation elements, as well as the synthesized radiation patterns in required directions. Upon changing a radiation pattern, its form and amplitude-phase distribution change in directions other than those specified. The coverage area is re-determined upon changing any of the characteristics. The displaying of the coverage area information can be turned off. An example of using the developed application for synthesizing a communication system with an aircraft is presented.

Conclusion. The developed application significantly facilitates the synthesis of secondary radar communication systems with antenna arrays. In addition, the application can be used in training radio electronics specialists.

Keywords: PAA, antenna array, interactive visualization, communication system synthesis, secondary radar, Kotelnikov series, genetic algorithm

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Электродинамика, микроволновая техника, антенны

Оригинальная статья

Вариант реализации интерактивного приложения для синтеза систем связи с антенными решетками

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Аннотация

Введение. Современные системы радиолокации и связи содержат фазированные антенные решетки. Одной из задач синтеза указанных систем является формирование требований к входящим в их состав узлам, модулям и блокам. Для решения поставленной задачи необходимо построить зону действия и проанализировать влияние характеристик входящих устройств. Повысить качество анализа и синтеза столь сложных систем может применение интерактивной визуализации данных, которая требует достаточно быстрого вычисления характеристик.

Цель работы. Разработка интерактивного приложения для увеличения возможностей синтеза систем связи, содержащих антенные решетки, и улучшения характеристик синтезированных систем.

Материалы и методы. Для ускорения вычисления диаграмм направленности применено их представление для антенной решетки в форме, позволяющей использовать алгоритм быстрого преобразования Фурье. Для нахождения требуемых амплитудно-фазовых распределений применяются разложение в ряд Котельникова и генетический алгоритм.

Результаты. В разработанном приложении выводятся на экран амплитудно-фазовое распределение, диаграмма направленности линейной эквидистантной решетки и зона действия. Возможно интерактивное изменение амплитудно-фазового распределения в излучателях и диаграммы направленности в заданных направлениях. При внесении изменений в диаграмму направленности меняется амплитудно-фазовое распределение и форма самой диаграммы направленности в направлениях, отличных от заданного. Зона действия перестраивается при изменении любой из характеристик. При необходимости ее отображение может быть отключено. В статье приведен пример использования приложения при синтезе системы связи с воздушным судном.

Заключение. Применение разработанного приложения позволяет расширить возможности и существенно сократить время анализа и синтеза систем связи и вторичной радиолокации с антенными решетками. Кроме того, приложение используется для подготовки специалистов для предприятий отрасли.

Ключевые слова: ФАР, антенная решетка, интерактивная визуализация, синтез систем связи, вторичная радиолокация, ряд Котельникова, генетический алгоритм

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Introduction. This article considers issues associated with a progressive increase in the functional complexity of electronic equipment and, as a consequence, with the need for visualizing various characteristics when solving the problem of synthesizing communication systems.

The development of complex systems, such as integrated electronic equipment, involves the analysis of a significant amount of heterogeneous data obtained as a result of mathematical modeling and field experiments. To this end, the obtained data must be presented in a form convenient for analysis and allowing varying initial parameters directly during the analytical process. Given the performance of modern computers, this can be achieved using the method of interactive data visualization. This method offers a number of advantages, such as the possibility of analyzing data in a real-time manner, which is essential when, e.g., setting up equipment for use or its further operation.

Almost all modern computer-aided design (CAD) systems are supplied with interactive visualization tools [1-3]. Some of them are applicable for solving specific tasks in individual fields, while others provide tools for solving a wide range of problems. The latter systems require careful tuning and rely on their own original mathematical models.

The present article describes the implementation of software for solving problems arising in the development of radio communication systems incorporating phased array antennas (AA). The concept of the proposed software is based on the simultaneous display of all data related to the solution of the problem and their interactive management [4].

A number of software products are currently used to facilitate the synthesis of communication systems. The main advantage of the AREPS (Advanced Refractive Effects Prediction System) [5] consists in the consideration of electromagnetic wave propagation for obtaining the coverage area of radioelectronic equipment. Similar capabilities are available in the Systems Tool Kit (STK) [6].

Commercial software packages for calculating radio lines and coverage areas are numerous. One such example is the *Albatross* CAD produced by the *Severnaya Corona* Information Space Center [7]. Although having a number of useful properties, these software products (SP) are either functionally redundant and, therefore, expensive or inaccessible due to, e.g., export restrictions. Therefore, the task of creating SP of the indicated type remains relevant. In addition, interactive visualization tools can be used in training students in respective specialties to ensure the generalization, accumulation and promotion of knowledge.

One of the key questions in the design of AA systems consists in the need to calculate the amplitude-phase distribution (APD) for a given radiation pattern (RP), i.e., to solve the inverse problem.

After obtaining the APD, it is necessary to determine the impact of error involved in setting the amplitude and phase in the antenna channels on the array RP. The deviations of the APD from the calculated value can be caused by at least two reasons: the discreteness of the phase shifters/attenuators and the nonidentity of their characteristics. The discreteness factor can be taken into account relatively straightforwardly using, e.g., a special Matlab software module [8]. The nonidentity factor is associated with the design of the antenna elements and the scatter of parameters during their manufacture and installation in the system. After the assembly and installation of AAs, particularly those having a small number of elements, their setup or calibration is performed [9, 10]. As a result, the actual APD will always be different from the calculated value.

This article presents a tool for evaluating the effect of errors arising during setting the amplitude and phase in the array channels on the radiation pattern (RP) of this array, as well as on the coverage area of the respective communication or radar system.

Methods. Two main types of algorithms – optimization and direct – are currently used for determining the APD necessary for the synthesis of an RP with a given shape. Optimization methods approximate the RP to a given iteratively. Direct methods are aimed at obtaining the APD via solving an equation. These methods are described in detail in [11]. Unfortunately, both approaches have a number of drawbacks, which have been extensively described in previous studies. These drawbacks impede the creation of a unified method for determining the APD. The mathematical core of the proposed application is formed by a genetic-based algorithm [12] and an improved direct algorithm based on the expansion of RP in the Kotelnikov series [13–15].

Before describing specific features of these algorithms, it should be mentioned that no radio engineering methods described in [16, 17], i.e., Fourier series, can be sufficient for solving synthesis problems, since, as a result of inverse transformation, APD values important for the RP formation are obtained at nodes outside the AA coverage area. For solving the analysis problem, the method of Fourier series is applicable from two points of view. Firstly, since the array factor is formed by the Fourier transform and given APD, the RP can be calculated using the FFT algorithm. Secondly, in the presence of diffraction maxima, synthesis is carried out only in the actual angle region determined as a result of the Fourier transform. In the remaining angle range, the spatial spectrum described by the array modulus is repeated, which is manifested in the appearance of diffraction maxima.

The use of FFT significantly facilitates the application of optimization methods. In particular, this is how RPs are actually formed at each iteration in the algorithm [9]. However, this algorithm accounts for neither the wavelength nor the array spacing, which required the addition of a scale angle difference:

$$\sin \vartheta_s = \frac{\lambda(1-u)}{f_s d} - \frac{\lambda(1-u_{av})}{f_s d},$$

where ϑ_s is the angular coordinate depending on the λ wavelength and the d array spacing; f_s is the sampling rate; $u = 1, 2, \ldots, f_s$ is the generalized coordinate.

A number of difficulties were identified while writing a program according to the algorithm proposed in [13, 14]. Unfortunately, this algorithm worked unsatisfactorily under a small number of emitters and such inter-emitter distances when diffraction maxima appear. Therefore, the following improvement was introduced: the integration limits were taken from the RP obtained using FFT. It should be noted that the algorithm from [13, 14] exhibits a somewhat higher functionality than that implied in its name, since it is capable of determining any RP value, rather than just forming a zero. To this end, such a level of auxiliary RP should be selected that could give the desired value after subtracting it from the main RP. A consistent and repeated use of the improved algorithm ensures not only the generation of several zeros, but also the synthesis of the required RP. As a result, the algorithm acquires the characteristics of optimization algorithms.

The methods presented in this article are well justified both in physical and computational terms.

Results. In order to demonstrate the operation of the proposed software application, let us obtain APD for an 8×8 AA with RP with the possibility of scanning in the azimuthal plane and a cosecant RP in elevation plane. Let the frequency be equal to 2.5 GHz and the distance between the emitters to be half the wavelength. In a more detailed synthesis, the distance between the emitters must be selected empirically.

Fig. 1 represents the interface of a program window. Further, only fragments of this window displaying the results of the software module are provided.

Let us begin by considering the elevation plane and applying a genetic algorithm. Fig. 2 shows the given envelope (red lines) and the obtained APD

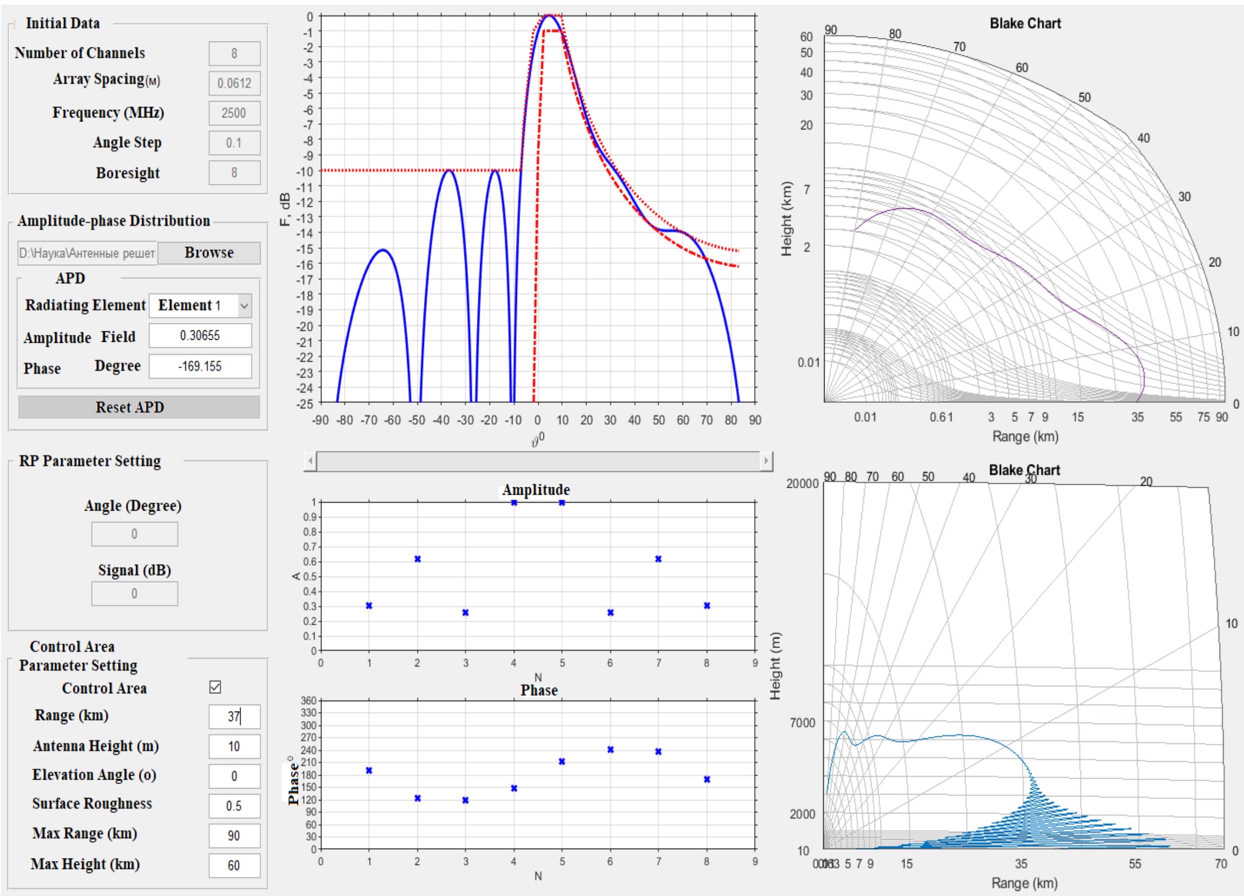

Fig. 1. Program Interface

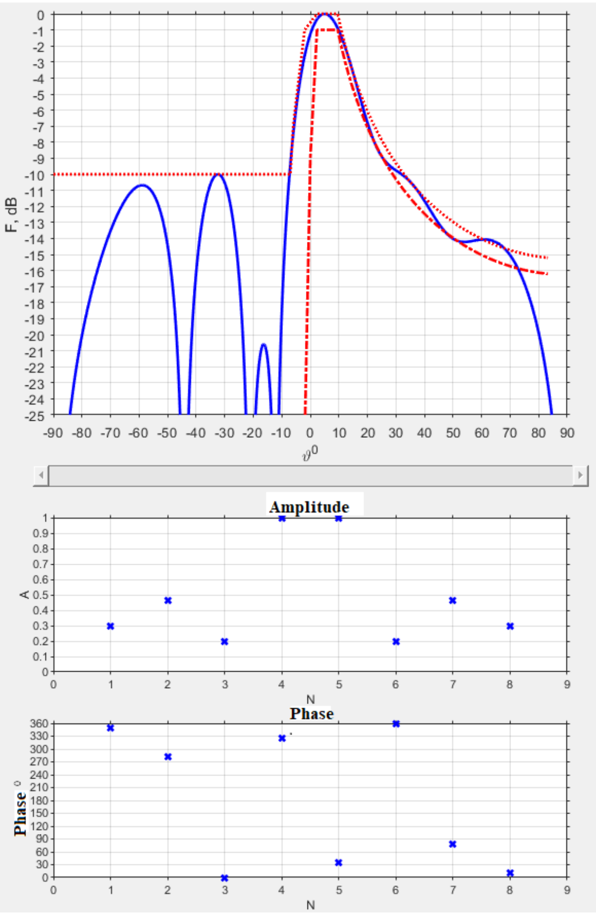

Fig. 2. Envelope and the Result of a Genetic Algorithm Optimization

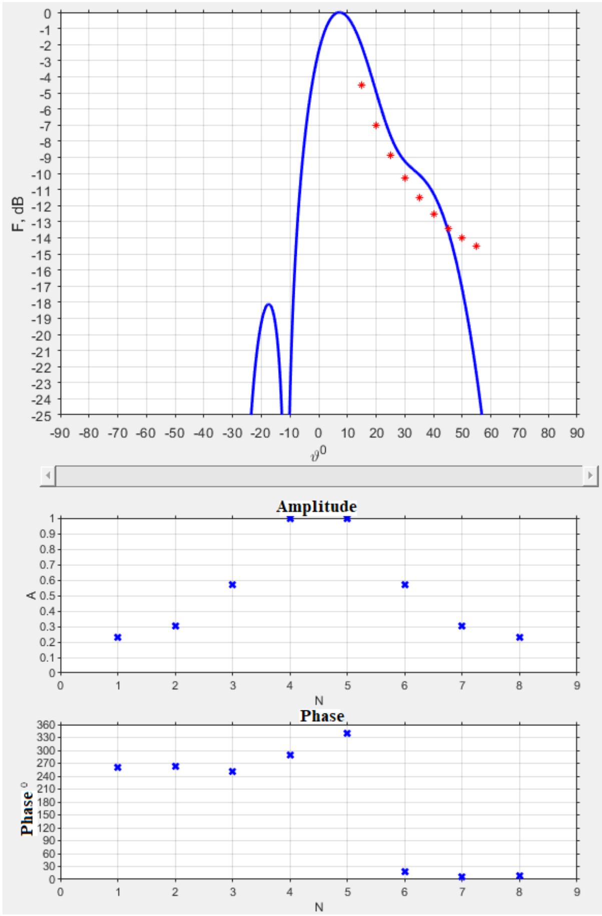

Fig. 3. Radiation Pattern and Amplitude Phase Diagram as a Result of the Nine Time Application of the Direct Synthesis

with RP (blue line). It should be noted that the algorithm, as a rule, converges rather gradually, resulting each time in a new APD slightly different from the previous one.

Provided that less stringent requirements are set for the envelope and small adjustments to the algorithm are made, a symmetric amplitude and an antisymmetric phase distribution can be obtained, as shown in Fig. 1.

A similar result is achieved when a direct algorithm is applied several times in succession. Figure 3 demonstrates the RP and APD obtained after applying the algorithm nine times. An equal-amplitude APD with a phase slope corresponding to the RP deviation by 8° from the normal was taken as the initial value. In Fig. 3, the substituted values are marked by asterisks. The direct algorithm can be improved and adapted for solving problems of synthesizing an RP of a given shape, as described in [14].

Finally, let us consider an antenna with a symmetric amplitude and an antisymmetric phase distribution, since this simplifies the design of distribution systems (see Fig. 1). The corresponding RP and coverage are also provided in Fig. 1. The coverage area is one of the most important results obtained during the synthesis of communication systems; therefore, it should always be displayed on the screen. In addition, by changing such parameters as the operational range (dependent on several factors) and underlying surface properties, changes in the coverage area can be detected and additional RP requirements put forward.

Let us proceed to the synthesis of RP in the azimuthal plane. Here, the direct algorithm is applied to form a deep zero in the direction of 20° (Fig. 4). The APD represented in Fig. 1 and 4 are used for constructing a three-dimensional RP (Fig. 5). The displaying of a three-dimensional RP allows evaluation of its features in order to select sections, which require a more detailed analysis. A case in point is the arrangement of emitters following a triangular pattern, when the diffraction maxima are displaced from the main planes or, in some cases, when the RP is folded into a funnel during scanning.

Conclusion. In summary, the developed software tool can be applied:

– to obtain numerical results necessary for the synthesis of communication and radar AA systems;

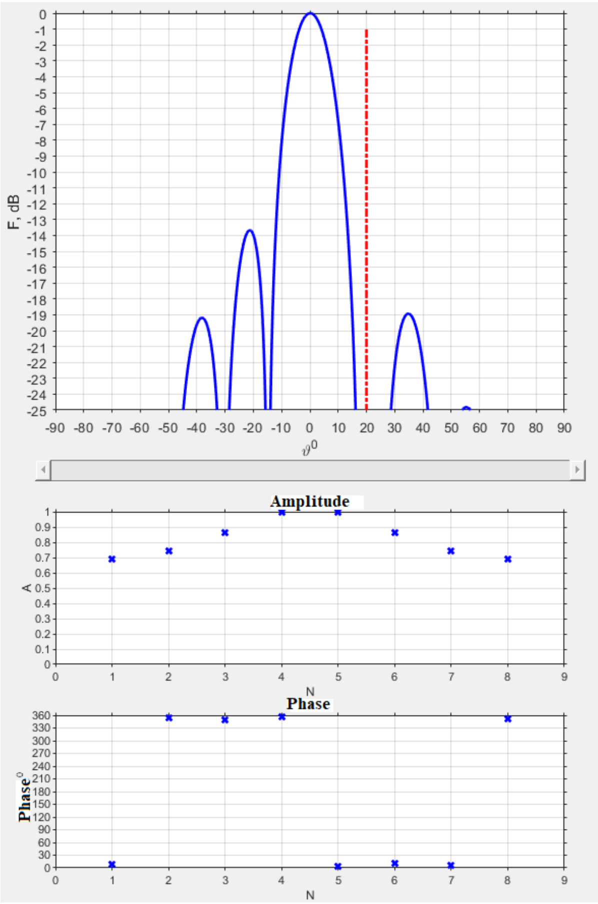

Fig. 4. Radiation Pattern and Amplitude Phase Diagram in the Azimuthal Plane

– to assess the effect of amplitude and phase setting errors in the AA channels both on the antenna RP and the system coverage area;

– to visualize characteristics of complex systems, thus reducing the probability of design errors.

Suggestions for future research are mainly related to increasing the functionality of the software module. Among them are the following.

The RP roughness as a result of diffraction at a carrier, including an electrically large carrier, affects the coverage area significantly. Therefore, when constructing the coverage area, the RP of the on-board antenna must be taken into account.

In the proposed software module, the emitter RP is approximated by a certain degree of cosine. In order to clarify the results, an effective classical approach should be applied. First, the emitter RP should be calculated or measured in the presence of neighboring units terminated into matched loads. Then, the resulting partial RP is to be substituted as the emitter RP.

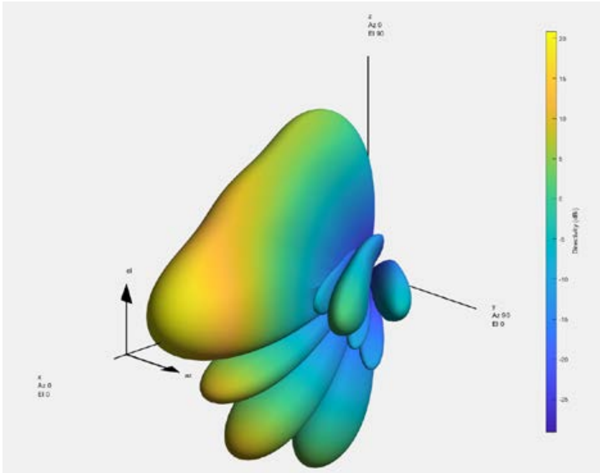

Fig. 5. Three-dimensional Radiation Pattern

Since the RP synthesis of antenna arrays represents the task of constructing a spatial filter, all developments achieved in the field of digital signal processing should be employed to design additional software modules. Moreover, the question of the suitability of the presented methods for searching faulty elements in AAs according to measurements in the far-field region requires elucidation. In addition, the proposed approach can be improved by adding the possibility of accounting for the properties of the underlying surface and factors affecting the propagation of radio waves.

One prospective developmental approach consists in the application of the proposed RP synthesis method for creating a sequence for training neural networks used in solving adaptation problems [18].

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