ADAPTATION ALGORITHMS FOR SATELLITE COMMUNICATION SYSTEMS EQUIPPED WITH HYBRID REFLECTOR ANTENNAS

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Abstract. This paper reviews adaptation algorithms influenced by active interferences in satellite communication systems. A multi-beam antenna is suggested as an adaptive system; it is built on the basis of a hybrid reflector antenna with a 19-element array feed element, which incorporates a modified algorithm for radiation pattern synthesis used for suppressing targeted interferences. As a criterion for this synthesis, antenna gains are used at fixed points. As a result, the size of the objective function and time required for the synthesis can be significantly limited.

1. Introduction. Satellite communication systems are becoming increasingly important due to the immensity of service areas and the high availability factor – the ability to provide communication channels in any place on the globe in a short time period. This rapid technological development significantly increases requirements to satellite communication systems. Among the requirements are channel capacity enhancement, channel security, interference protection and flexible traffic. These requirements are especially relevant for the Russian Federation: its territory is considerably extended longitudinally, the population density in many areas is low, there are 11 time zones. The most effective method of implementing these requirements on satellites is the usage of multi-functional adaptive antennas with spatial selection.

However, the usage of these antennas also encounters a number of difficulties. Unlike the simpler classical antenna, the adaptive multi-antenna includes a high number of active expensive elements (controlled phase shifters, attenuators, control loops elements, etc). Consequently, it is necessary to take into consideration not only existing technical characteristics, but economical indicators for selecting an assembly method for these antennas.

Forming multiple beams and implementing spatial selection is possible either on the basis of an adaptive phased array or on the basis of hybrid reflector antennas [1].

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Adaptive phased arrays have significant advantages over other types of antennas in speed maintenance and multitasking [2]. Adaptive phased arrays with digital beamforming enable flexible control over the direction of the main maximums in each of the partial radiation patterns for a wide range of angles; they are capable of forming deep nulls in radiation patterns in the direction of the source of interference. However, adaptive phased arrays weigh more and are larger in size; they are equipped with more complicated hardware – particularly the beamforming arrangement. These factors, consequently, result in significantly higher costs for these systems [3].

The scan angles for adaptive hybrid reflector antennas are smaller but this disadvantage is insignificant for geostationary spacecraft and spacecraft with high elliptical orbits and is fully compensated by the simpler design.

In many situations it is more promising to use an antenna array having a relatively small number of elements as a feed element for focusing the quasioptical element of the reflector. The primary antenna array is commonly known a feed cluster. Hybrid reflector antennas combine the advantages of highly efficient reflector antennas and antenna arrays. Hybrid reflector antennas enable the formation of tunable multipath radiation patterns and radiation patterns with a special shape; they provide the spatial filtering of signals and interferences; and they are capable of adapting to failures of the primary antenna array.

This class of antennas allows combining the advantages of reflector antennas – namely the simplicity of the aperture construction, the possibility of effective transformation and the flexibility typical of adaptive phased arrays. The technical specifications of hybrid reflector antennas are equivalent to those of adaptive phased arrays, the first being significantly less expensive due to the reduction of the number of active elements.

In such antennas the system of adaptation and forming radiation patterns should be conducted in two modes – the multi-beam mode and the contour beam.

In the first case, the coverage of the required service area is provided by a set of narrow beams. The application of a multi-beam radiation pattern enables multiple uses of the frequency resource due to spatial isolation between the beams. In the second case, a radiation pattern which exactly repeats the system’s service area is formed. The pattern flexibly redistributes power within a given service area.

Technically, it is possible to arrange these modes either for simultaneous or for individual use. Economically, the combination of these modes is more advantageous since one primary antenna array can be used for both modes.

2. Adaptation algorithms for hybrid reflector antennas

The following antenna arrangement can be proposed as a variation of the adaptive hybrid reflector antenna. The antenna array of the feed element is built from 19 feed elements using the cluster principle – each of the 7 beams of the antenna is formed by a set of feed elements (the cluster) (Fig. 1) [4]. Each cluster, consisting of 7 feed elements, is powered in-phase, half of the radiated power is supplied to the central feed element and half is redirected to peripheral feeds.
Figure 1. Beamforming principal based on cluster scheme of the primary antenna array.

Such a scheme enables beamforming for 7 beams in the radiation pattern for different frequencies, preventing the beams from contacting one another. Nullforming in the radiation pattern of one cluster is possible by powering one of the feed elements in antiphase (Fig. 2) [5]. This method, however, has one significant disadvantage – the null is formed at a fixed direction.

Powering the feed element antiphase results in a significant signal loss: up to 20% from the nominal service area (Fig. 2). Furthermore, to suppress additional interference it is necessary to power an additional feed element in antiphase. This would result in further degradation and the complete loss of antenna characteristics.

Nulling radiation patterns in the direction of the side lobes is possible by increasing the number of feed elements, which form the radiation pattern of a hybrid reflector antenna. However, this method is not always effective, since it may lead to a complication of the antenna’s structure and an increase in the weight and the size of the antenna.

Figure 2. Interference suppression from the direction of main lobe in a hybrid reflector antenna by powering one of the cluster members antiphase.

To improve the performance of the antenna, let’s synthesize the amplitude-phase distribution of the hybrid reflector antenna’s primary array. This will enable to synthesize the desired shape and nulls of the radiation pattern not only in the direction of the main lobe, but
in the direction of the side lobes as well. The number of feed elements in the array remains unchanged.

Generally, the radiation pattern in the far field of a multibeam antenna during performance in a cluster can be written as

\[ |E(W_j, \theta, \phi)|^2 = \sum_{j=1}^{N_{\text{max}}} E_{ij} \cdot W_j \]

where \( W_j = A_j \cdot e^{j\phi_j} \) is the weighted factor of the feed element. \( E_{ij} \) is the radiation pattern from \( j \) (feed factor) in \( i \) (direction of observation). \( |E(W_j, \theta, \phi)|^2 \) is the required radiation pattern of the antenna.

It is necessary to limit the amplitude of feed elements depending on the normalization condition of cluster power

\[ \sum_{j=1}^{N_{\text{max}}} A_j^2 = 1. \]

\( E_{ij} \) is the beforehand known value; it further transforms into the constant for the particular point \( \theta_i, \phi_i \) during the synthesis of the adaptive phased arrays. In order to make calculations of the adaptive phased arrays less time consuming, it is possible to limit function (1) by a set of points, which are determined programmatically. A desired value of the signal level for each point is defined.

The set of weighted coefficients can be given as a vector

\[ W = [W_1, W_2, \ldots, W_j]^T. \]

The calculation is carried out in a set of points to limit the size of the objective function and the duration of the synthesis of the adaptive phased arrays. This decreases the time needed for calculating the required adaptive phased arrays and improves the efficiency of the whole system.

The directive gain of the antenna in the given points (targets) is taken as a criterion for synthesizing radiation patterns. Additionally, it is necessary to modify the algorithm due to the limited number of points and the need for nullforming in radiation patterns. Let’s introduce a concept of the wave channel “target”, which will increase or decrease the signal level for a given “target”:

\( w > 0 \) – the increase of signal level at a given point, tends to the maximum possible value.

\( w < 0 \) – the signal suppression at a given point, tends to the lowest possible value.

Based on the aforementioned, we can write the objective function of the algorithm for synthesizing the cluster of adaptive phased arrays as

\[ f_i = w_i \left( |E(\theta, \phi)|_{\text{obs}, j}^2 - |E_j(\theta, \phi)|_i^2 \right), \]
where \( w_i \) is the weighted factor of the “target”. \( |E(\theta, \varphi)_{\text{wmin}}|^2 \) is the required value of the signal level for a given point in space. \( |E_i(\theta, \varphi)|^2 \) is the achieved value of the signal level for a given point of space.

Thus, there is a set of values of \( f_i \), corresponding to the axis set in a required service area.

The purpose of this algorithm is to minimize the value of function \( F(x) \). The parameter value is tried by successive iterations to achieve the minimum value of the objective function.

\[
F(\tilde{x}) = \max\{ f_1(\tilde{x}), f_2(\tilde{x}), f_3(\tilde{x}), ..., f_k(\tilde{x}) \}.
\]

The equal-amplitude cophasal distribution of antenna arrays (arrays containing 19 feed elements) is taken as the first iteration. Then, the algorithm calculates the absolute gain for each given point on the basis of equal-amplitude distribution, establishing the maximum value of the difference between the required and the actual gain \( \Delta E = |E(\theta, \varphi)_{\text{wmin}}|^2 - |E_i(\theta, \varphi)|^2 \).

From a set of \( \Delta E \) the point at which there is maximum difference in the initial state and the desired (\( \Delta E_{\text{max}} \)) is found; after this the gradient vector \( \nabla E \) in the point of maximum difference is determined. Next, the vector parameter \( W \) is replaced with its new parameter value of \( W_i = W_0 \pm \alpha \cdot \nabla E \), where \( \alpha \) is the step size defined by software. This process is repeated as long as \( \|W_i - W_0\| < \varepsilon \) (\( \varepsilon \) is given before the beginning of the synthesis process), i.e. until the difference between the desired gain value and the actual gain value for each “target” achieves minimum changes. The number of iterations can be set programmatically, or the algorithm will automatically stop working after a minimum in changes has been attained.

**Figure 3.** Suppressing interference in hybrid reflector antenna from the main and the first side lobes.

Calculation for a cluster of adaptive phased arrays with 7 feed elements is performed using the synthesized algorithm. The calculation was performed for a case of interference in the direction of the main lobe and the direction of the first side lobe (Fig. 3).
3. Conclusion

The following conclusions can be made from the research:

1. Hybrid reflector antennas, equipped with the proposed algorithm for adaptive phased arrays synthesis, have provided nulling in radiation patterns in the direction of the main lobe and in the direction of side lobes of minus 45–50 dB.
2. A decrease in the signal level at 10% of the total service area has been recorded.
3. An insignificant difference in the signal level in the main lobe (not exceeding 0.3 dB) has been observed. It was provoked by setting the signal level requirements in the service area which hadn’t been affected by the interference.

Thus, the proposed adaptation algorithm for hybrid reflector antennas enables us to fulfill all current requirements for satellite communication systems with minimal expenses.

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