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ADAPTIVE ANTENNA ARRAY WITH ANGULAR AND POLARIZATIONAL SIGNAL AND INTERFERENCE DISCRIMINATION IN A SPACE COMMUNICATIONS CHANNEL

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A mathematical model is developed for an adaptive antenna array with angular and polarizational discrimination (AAA/APD) of radio signals. The model is employed to study the operation of such an array in a space radio communications link when receiving completely polarized useful signal and interference in the presence of additive noise. It is shown that AAA/APD provides an average gain in the signal-to-(noise + interference) ratio of at least 10 dB even in the most unfavorable situation in which the signal and interference come from the same direction.

INTRODUCTION

The design principles for adaptive antenna arrays (AAA) aimed at improving the quality of useful signal reception in the presence of interference are well known [1]. Most frequently the distinctive features of the received electromagnetic fields are their frequency spectrum or incidence direction. However, field polarization can also be such a feature [2–5].

Very promising is the joint utilization of the incidence angle and polarization as combined distinguishing features of different fields with the same frequency, because in such a case the number of independent parameters in the space of real variables used to describe the vector field $\mathbf{E}(\omega)$ increases from two to four: in addition to the angles of elevation (ϑ) and azimuth (φ), which define the wave incidence direction, we have a field phasor $P = \operatorname{Re} P + i \operatorname{Im} P$ describing the field polarization.

In this case the AAA pattern must be defined in a space of four variables as $F(\vartheta, \varphi, \operatorname{Re} P, \operatorname{Im} P)$. Obviously, this significantly broadens the possibilities for separate reception of different waves at the same frequency.

PROBLEM FORMULATION

One possible method for optimal processing of a mixture of useful signal and interference is to discriminate them by the combined angular and polarization features. This method can be implemented with an appropriate adaptive antenna array.

Let an adaptive antenna array with the angular and polarizational discrimination (AAA/APD) be located on board an artificial Earth satellite which is placed in a geostationary orbit. The vector field sources of the useful signal and several interferences of the same frequency are located at the Earth surface visible from the satellite. Let us idealize the space communication link, assuming no scattering and depolarization of the waves which propagate over it.

Let us assume that the polarization of the interferences is *a priori* unknown, while that of the signal is known.

The purpose of the present study is:

(1) to formulate the principles of the AAA/APD structure and operation in a radio link with no *a priori* information about the interference;

(2) to create a mathematical model of the AAA/APD and to investigate, using this model, the efficiency of such an array in a space communications link.

STRUCTURAL DIAGRAM OF THE AAA/APD

The AAA/APD can be designed in such a way that its pattern could be optimized independently for the reception of the useful signal and the interference. Such a design allows one to provide a constant maximum power of the useful signal and, in general, a variable minimum power of the interference at the AAA output. In order to achieve this goal, the AAA/APD is composed of two subarrays (Fig. 1), one of which (the signal antenna array, SAA) is designed for optimal reception of the useful signal. Each SAA element is a pair of orthogonal dipoles connected by an adding system with a complex weight factor W_γ (not shown in Fig. 1) which is the same for all elements.

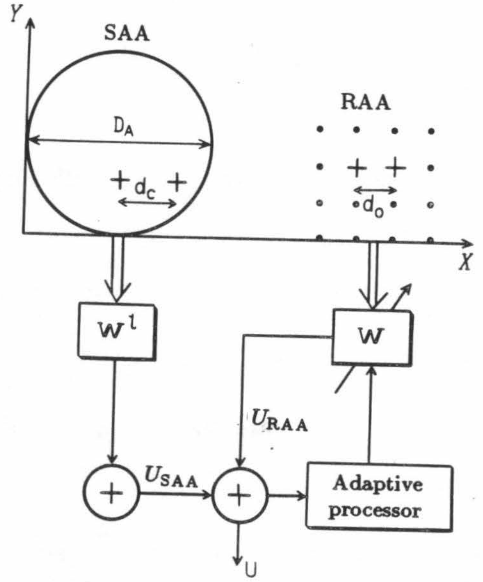

Fig. 1

Structure of the adaptive antenna array with angular and polarizational discrimination of electromagnetic fields. The SAA and RAA are composed of polarization-sensitive antenna elements (crosses) arranged in the circular and the square windows, respectively; $\mathbf{W}^l$ is the vector of weight factors in the system that forms the SAA lobe number l; $\mathbf{W}$ is the controlled vector of weight factors which combines the SAA and RAA to produce the AAA; U_{SAA} and U_{RAA} are respectively the SAA and RAA responses; U is the overall AAA response.

The SAA elements are spaced in two orthogonal directions X, Y at an increment d_s; the array consists of 49 antenna elements arranged in a circle of diameter $D_A = 8.5d_s$ and combined in a single device by a weight-adding system with a set of weight factor vectors $\mathbf{W}^l$. Each of these vectors provides SAA phasing for the reception of plane wave from a specified direction. The number of antenna elements and the diameter D_A are determined by the requirements for the width of the main SAA lobe and the level of its sidelobes.

The SAA pattern has a multilobe structure. The total area serviced by the space communications system on the Earth surface is composed of multiple circular local zones. From the geostationary orbit this area has the angular size ±12°. The requirement for a uniform distribution of the radio signal energy on the Earth surface leads to the need to have a hexagonal structure of the overall SAA pattern (Fig. 2). The

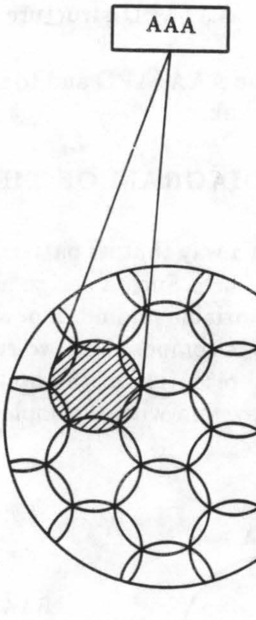

Fig. 2

The overall and local areas of radio servicing by a geostationary satellite on the Earth's surface.

number of local zones (the number of lobes in the overall SAA pattern) is subject to the condition

$$l = 1 + 3n(n+1), \quad n = 1, 2, 3, \ldots$$

In our SAA model we assume $l = 19$; in this case, the diameter D_l of a local zone is related to the total service area diameter D by

$$D_l = D/2\sqrt{3}.$$

The second subarray (the reference antenna array, RAA) is aimed at isolating the reference signal required for AAA operation, i. e., a copy of the interference. The RAA is composed of polarization-sensitive antenna elements similar to those of the SAA. The two subarrays are united into a single adaptive antenna array which provides automatic suppression of several interferences about which no *a priori* information is available. The maximum number of independent interferences which can be suppressed by the AAA is equal to the number of antenna elements in the RAA.

In the model at hand, the number of antenna elements in the RAA is 16, and they are arranged equidistantly on the plane along two orthogonal directions X, Y with a spacing d_0. The output voltages from the loads of the RAA antenna elements are scalarly multiplied by 16 controllable complex weight factors (vector $\mathbf{W}$ in Fig. 1) and summed, forming the RAA output signal.

MATHEMATICAL MODEL OF THE AAA/APD

Let a plane elliptically polarized wave be given in the local basis $(\mathbf{e}_\vartheta, \mathbf{e}_\varphi, \mathbf{e}_\rho)$ by two projections of the vector $\mathbf{E}$: E_ϑ and E_φ.

Let us determine the response of the SAA phased for the direction (ϑ_l, φ_l) to a wave coming from the direction (ϑ, φ). This response will correspond to one lobe, with the index l, of the multilobe SAA pattern

$$U_{\mathrm{SAA}} = F_{\mathrm{SAA}}\{W_1 E_x + W_2 E_y) = F^l_{\mathrm{SAA}} \mathbf{W}^T_{\mathrm{SAA}} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = F^l_{\mathrm{SAA}} \mathbf{W}^T_{\mathrm{SAA}} \mathbf{L} \begin{pmatrix} E_\vartheta \\ E_\varphi \end{pmatrix}, \qquad (1)$$

where $F^l_{\mathrm{SAA}} = \sum_{j=1}^{49} W^l_j \exp\{-i\mathbf{k}(\vartheta,\varphi)\mathbf{r}_j\}$ is the response to a plane scalar wave coming from the direction (ϑ,φ), $\mathbf{W}^l = \{W^l_j\}$ is the vector of weight factors which provides the SAA phasing to the direction (ϑ_l,φ_l); $W^l_j = \exp\{i\mathbf{k}(\vartheta_l,\varphi_l)\mathbf{r}_j\}$; $\mathbf{W}_{\mathrm{SAA}} = \left\{\begin{matrix} W_1 \\ W_2 \end{matrix}\right\}$ is the column vector of weights in the system which adds the voltages on the loads of the orthogonal dipoles of the antenna elements; $\mathbf{r}_j$ is the radius-vector of an SAA element; $\mathbf{L} = \begin{pmatrix} \cos\vartheta\cos\varphi & -\sin\varphi \\ \cos\vartheta\sin\varphi & \cos\varphi \end{pmatrix}$ is the matrix transforming the field $\begin{pmatrix} E_\vartheta \\ E_\varphi \end{pmatrix}$ into the field $\begin{pmatrix} E_x \\ E_y \end{pmatrix}$, based on the transformation matrix for the transition from the local basis $(\mathbf{e}_\vartheta, \mathbf{e}_\varphi, \mathbf{e}_\rho)$ to the coordinate system $\{X, Y, Z\}$ (Fig. 3).

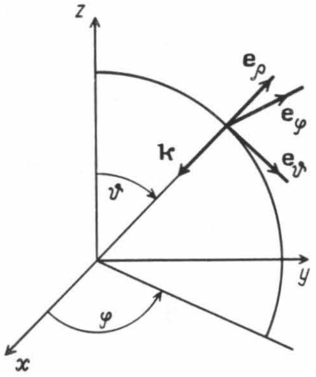

Fig. 3

The AAA coordinate system X, Y, Z and the local basis attached to the incoming wave.

Let us discuss the role of wave polarization in the formation of the SAA pattern. We describe polarization by the phasor of the field $\mathbf{E}$ in the local basis (e_ϑ, e_φ):

$$P = E_\vartheta / E_\varphi .$$

Using the definitions of the phasor, the real and the complex field amplitudes,

$$|E|^2 = |E_\vartheta|^2 + |E_\varphi|^2, \quad E = |E|e^{i\Phi}, \quad \Phi = \arg E,$$

we can represent formula (1) in the form

$$U_{\mathrm{SAA}} = F_{\mathrm{SAA}} \mathbf{W}^T_{\mathrm{SAA}} \mathbf{L} \begin{pmatrix} P \\ 1 \end{pmatrix} E / [(1 + |P|^2)]^{1/2}. \tag{2}$$

Then the expression

$$\widehat{F}_{\mathrm{SAA}} = F_{\mathrm{SAA}} \mathbf{W}^T_{\mathrm{SAA}} \mathbf{L} \begin{pmatrix} P \\ 1 \end{pmatrix} \Big/ [(1 + |P|^2)]^{1/2} \tag{3}$$

is the SAA response to a unit polarized wave with the phasor P coming from the direction (ϑ,φ), i. e., its space-polarization pattern which is specified in the space of four real variables ϑ, φ, $\operatorname{Re} P$, and $\operatorname{Im} P$.

The space-polarization pattern of the RAA is defined similarly,

$$\widehat{F}_{\mathrm{RAA}} = F_{\mathrm{RAA}} \mathbf{W}^T_{\mathrm{RAA}} \mathbf{L} \begin{pmatrix} P \\ 1 \end{pmatrix} \Big/ [(1 + |P|^2)]^{1/2}, \tag{4}$$

where $F_{\mathrm{RAA}} = \sum_{q=1}^{16} W_q \exp\{i\mathbf{k}(\vartheta,\varphi)\mathbf{r}_q\}$; $W = \{W_q\}$ is the vector of weight factors controlled by the adaptive processor; $\mathbf{r}_q$ is the radius-vector of an RAA element; and $W_{\mathrm{RAA}} = \begin{pmatrix} W_2^* \\ -W_1^* \end{pmatrix}$.

The SAA and RAA are combined into a single device, the AAA/APD, by the vector of complex weight factors **W**, the adder, and the adaptive processor. The space-polarization pattern of the total AAA is the sum of the two patterns:

$$\widehat{F}_{\mathrm{AAA}}(\mathbf{W},\vartheta,\varphi,P)=\widehat{F}_{\mathrm{SAA}}(\vartheta,\varphi,P)+\widehat{F}_{\mathrm{RAA}}(\mathbf{W},\vartheta,\varphi,P). \tag{5}$$

The AAA/APD response to a sum of M fields $E_m(\vartheta_m,\varphi_m,P_m)$ is

$$U=\sum_{m=1}^{M}\widehat{F}_{\mathrm{AAA}}(\mathbf{W},\vartheta,\varphi,P)E_m(\vartheta_m,\varphi_m,P_m). \tag{6}$$

Let the superposition of M fields consist of the field of a single useful signal E_s and $M-1$ interference fields E_i. In our AAA model the following fundamental condition is implemented

$$\widehat{F}_{\mathrm{RAA}}(\mathbf{W},\vartheta_e,\varphi_s,P_s)E_s(\vartheta_s,\varphi_s,P_s)\equiv 0. \tag{7}$$

In this case it follows from Eqs. (5) and (6) that the AAA/APD response to the mixture of a single signal and $M-1$ interferences is

$$U=U_s+U_i(\mathbf{W}), \tag{8}$$

where $U_s=\widehat{F}_{\mathrm{SAA}}E_s$ is the SAA response to the useful signal and $U_i(\mathbf{W})=\sum\limits_{m=2}^{M}\widehat{F}_{\mathrm{AAA}}E_m$ is the response to $M-1$ interferences.

In accordance with (7), the mean output power of the AAA/APD is

$$\langle|U|^2\rangle=\langle|U_s|^2\rangle+\langle U_sU_i^*(\mathbf{W})\rangle+\langle|U_i(\mathbf{W})|^2\rangle. \tag{9}$$

If the signal and the interferences are mutually uncorrelated, then $\langle U_sU_i^*\rangle=0$, and it follows from Eq. (9) that the AAA/APD minimum average output power corresponds to the condition $\langle|U_i(\mathbf{W}=\mathbf{W}_{\mathrm{opt}})|^2\rangle=0$. Thus, finding the optimal value of the vector $\mathbf{W}_{\mathrm{opt}}$ during the adaptation process, one can modify the AAA space-polarization pattern in such a way that no interferences will be present in its output response. Of course, the existence of noise and inaccuracies in satisfying condition (7) give rise to incomplete interference suppression, so the AAA/APD average output power will be only approximately equal to the useful signal power.

The weight vector $\mathbf{W}_{\mathrm{opt}}$ which provides a minimum of the AAA output power can be found with the aid of an adaptive processor which implements, for instance, the method of steepest gradient descent.

Let us denote the ratio of the useful signal average power P_s to the sum of average powers of the interference P_i and additive noise P_f by

$$\mu_i=\langle P_s\rangle/(\langle P_i\rangle+\langle P_f\rangle).$$

Let us introduce the ratio $\mu=\mu_2/\mu_1$, where $\mu_{2,1}=\mu_i$ at the output and input of the AAA, respectively. Obviously, μ characterizes the quality (or efficiency) of interference suppression by a given AAA and is an indirect measure of the precision of the optimal solution $\mathbf{W}=\mathbf{W}_{\mathrm{opt}}$ found.

OPERATING EFFICIENCY OF THE AAA/APD

Let us consider the typical and extreme (with respect to the parameter values of the problem) cases which may take place for a given configuration of an AAA/APD located on board a geostationary satellite.

The primary task of any antenna array is to improve the signal/(interference + noise) ratio at the input of the receiver device connected to it. The efficiency of AAA operation will equal unity if all the field parameters of the signal and interference by which they can be distinguished coincide. In order to illustrate the advantages of the AAA/APD, it is worthwhile to consider the conditions in which traditional AAA with angular discrimination fail to work, i.e., the case in which the signal and interference come from the same direction.

For more graphic presentation of our results, we shall specify the electromagnetic field polarization not by its phasor $P = \mathrm{Re}\,P + i\mathrm{Im}\,P$ but by two equivalent parameters: the ratio of the axes of the field polarization ellipse $\pm r$ (the $\pm$ signs define the rotation direction of the vector $\mathbf{E}$ in the wavefront plane) and the angle β between the major axis of the polarization ellipse and the direction $\mathbf{e}_\vartheta$ in the local coordinate system.

Let us discuss the AAA/APD operation in the following problem conditions.

1. The powers of signal and interference at a single antenna element dipole are equal ($P_s = P_i = 1$).

2. The signal polarization in the accompanying coordinate system is fixed, circular, with the vector $\mathbf{E}_s$ rotating rightward ($r_s = 1$).

3. The interference polarization in the accompanying coordinate system is arbitrary ($-1 \leqslant r_i \leqslant 1$; $\beta_i = 0°\text{–}360°$).

4. The signal incidence angles are fixed in the satellite reference system, $\vartheta_s = \varphi_s = 0$ (the signal source is at the center of the SAA pattern lobe with $l = 0$).

5. The interference incidence angles are in the ranges $0 \leqslant |\vartheta_i| \leqslant 12°$, $0 \leqslant |\varphi_i| \leqslant 360°$ in the satellite reference system.

6. The power of additive noise at a dipole of a single antenna element $\langle P_f \rangle$ is a variable parameter ($1 \leqslant \langle P_f \rangle \leqslant 10^{-4}$); the noise is normal, uncorrelated in space and time, with a zero mean and unit variance.

7. The signal, interference, and noise are mutually uncorrelated.

8. The signal and interference are completely polarized.

Figure 4 shows the calculated AAA/APD efficiencies in the worst case, i.e., when the signal and interference incidence angles are the same. Analyzing these graphs, the following conclusions can be drawn.

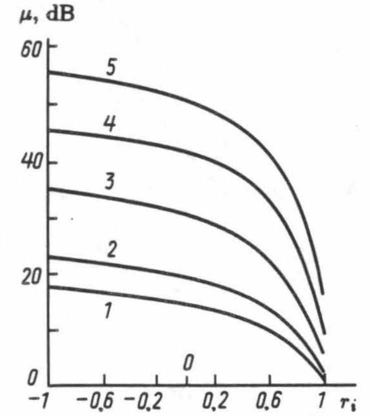

Fig. 4

AAA/APD efficiency as a function of interference polarization. The normalized power of additive noise at the AAA input, $\langle P_f \rangle = 1$ (1), 10^{-1} (2), 10^{-2} (3), 10^{-3} (4), and 10^{-4} (5).

1. The AAA/APD efficiency can be tens of decibels even for coinciding incidence angles but different polarizations of the signal and interference (about 5 to 50 dB).

2. The efficiency curve $\mu = f(r_i)$ is nonlinear, the value of μ falling sharply as the signal and interference polarizations become closer, but even at $r_i = 0.99$ and $r_s = 1$ the AAA/APD efficiency remains high ($\mu \approx 5$ to 20 dB, depending on $\langle P_f \rangle$).

The AAA/APD efficiency curves for different interference incidence angles are shown in Fig. 5 for $\vartheta_s = \varphi_s = \varphi_i = 0$, $\beta_i = 0$, and $\langle P_f \rangle = 10^{-4}$.

These data suggest the conclusion that the AAA/APD efficiency depends weakly on the incidence angle of an interference located within the satellite service area in a wide range of values of the quantity $\Delta r = |r_s - r_i|$ ($40\ \mathrm{dB} \leqslant \mu \leqslant 55\ \mathrm{dB}$); an exception is the region in which r_i and r_s are close: for $r_i = 0.99 r_s$, with the interference incidence angle varying in the range of $\vartheta_i = \pm 8°$, the function $\mu = f(\vartheta_i)$ varies between

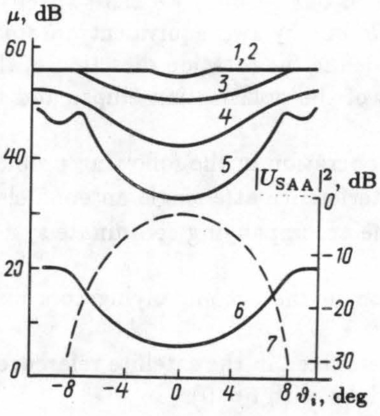

Fig. 5

AAA/APD efficiency as a function of interference incidence angle. The interference polarization $r_i = -1$ (1), -0.5 (2), 0 (3), 0.5 (4), 0.8 (5), and 0.99 (6); curve 7 is the main lobe of the AAA pattern.

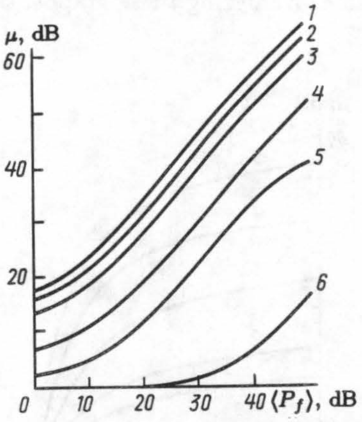

Fig. 6

AAA/APD efficiency as a function of additive noise power $\langle P_f \rangle$ at the array input. The interference polarization $r_i = -1$ (1), -0.5 (2), 0 (3), 0.5 (4), 0.8 (5), and 0.99 (6).

6 and 20 dB, the value of μ remaining greater than 6 dB even when the signal and interference incidence directions coincide.

The AAA/APD efficiency also depends on the relative level of additive noise. Figure 6 shows a family of curves $\mu = f(\langle P_f \rangle)$ for $\vartheta_i = 0$ and $r_i = -1$; -0.5; 0; 0.5; 0.8; and 0.99 (curves 1–6, respectively) demonstrating that

(1) the AAA/APD efficiency depends nonlinearly on the additive noise, especially when the r values for the signal and interference are close;

(2) the AAA/APD remains efficient ($\mu > 6$ dB) even under very unfavorable conditions, when the signal-to-noise ratio is 1 and the signal and interference incidence directions coincide; the only requirement for achieving this is a minor difference in the signal and interference polarizations ($|r_s - r_i| \sim 0.01$).

The data presented above characterize rather fully the capabilities for the discrimination of equal-frequency electromagnetic fields with the aid of a special type of AAA whose pattern is defined in the space of angles and polarizations. The discriminative capabilities of the AAA/APD are much greater than those of the traditional AAA with angular discrimination.

CONCLUSION

Space-polarization processing of multibeam electromagnetic fields opens new possibilities for designing various radio signal transmission and reception devices.

In the present work, a unique structure was proposed and a model was investigated for one such device, an adaptive antenna array with angular and polarizational discrimination; its main design principles are universal and can be used in the design of radio receiver devices intended for operation in space, tropospheric, and ionospheric communication links.

We have quantitatively evaluated the gain in the signal/(interference + noise) ratio provided by an AAA/APD operating on board a geostationary Earth satellite in various conditions. An important feature of the AAA/APD is its ability to receive the useful signal even in the case when the signal and the interference are coming from the same direction.

This ability is retained even for very weak signals, for which the signal-to-noise and signal-to-interference ratios in the communications channel are equal to 1. Even in such extremely unfavorable conditions, the AAA/APD provides a gain of about 3 to 18 dB in the signal/(interference + noise) ratio, thereby ensuring reliable reception of the useful signal.

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