Using Conformal Shape, Separate and Dynamical Apodization and Smart Antena Technology for Improving Array Characteristics

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Abstract

Three methods improving array characteristics have been discussed. Applications of these methods for communication satellites, HATP, ground based antennas for mobile communications and radars are considered. For the first method, techniques of calculation and main results have been presented, comparing characteristics of plane and conformal arrays. For the second method, advantages and disadvantage are considered and, finally, some elements of the smart array technology are discussed.

1. Introduction

For the first time applications of active arrays are getting wide recognition in space, aviation and ground-based systems. The examples of such applications are multi beam antenna for communication satellite, multi beam antenna for high altitude telecommunication platform (HATP) [1], ground based smart antenna for mobile communications, radars etc.

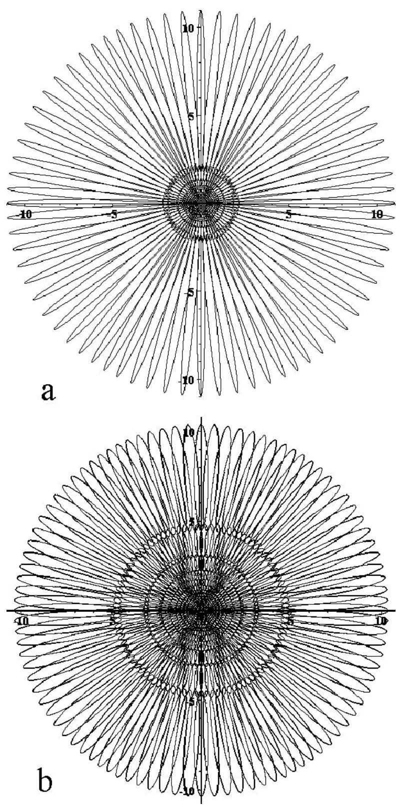

Fig. 1. Cell distribution pattern for plane (a) and conformal (b) array (R=10H).

The three methods of improving array characteristics are considered in the paper. These methods do not pretend to revolutionary but they have been used by authors in research and experimental development and give good results. The paper volume does not allow to describe these method in detail but the main practical aspects have been presented. The details can be found in other authors' papers. Finally, we note that method described in the sections 2 is germane to ameliorate radar characteristics.

2. Conformal arrays

Large part of arrays has plane surface. The main limitation of coverage radius of such arrays is a very big ratio of outer cells area to area of central cells. This effect caused by rapid increasing beam angle with the deflection from the main direction. A typical cell distribution pattern is presented in Fig. 1a. The plotted cells borders mean curves where energy-flux density decreases by 2 times. In our calculations we have taken R=10H and $D=15\lambda$, where R is the coverage radius and H – antenna altitude, D – antenna diameter and λ – wavelength. In that case the coverage radius of low earth orbit (LEO) satellite operating at the altitude 200 km is 2000 km; for HATP – R=200 km [1]; for mobile communication antenna placed on 60 m mast – R=600 m. The calculations yield the length of outer cells is about 8H and $S/S_I \approx 500$, where S is the area of the outer cells and S_I is the area of the central cell. Such big ratio means that either the antenna cannot service all subscribers in the outer part of coverage or antenna can service outer part but in the central area potential beams capacity is much greater than what it required. The second limitation of plane array is a high level of outer beams sidelobes. Furthermore the power flux density in the centre of the outer beams is approximately $(R/H)^2$ times greater the magnitude of the central beams; the ratio $(R/H)^2$ is equal 100 for R=10H. The sidelobs of outer beams can be directed to the central cells and their level increases proportionally to this ratio. In additional, we note one more aspect of this problem. The authors of the paper [4] show that for traditional mobile network the multi beam antenna gives an opportunity to reduce the frequency reuse factor down to 3. But practically such pattern cannot be exploit due to high sidelobes level of outer beams. The experimental development shows that array with $D = 6\lambda$ and the maximal beam deflection angle 81 needs at least 11 frequencies groups. Using conformal array can reduce both limitations. Moreover separate beam apodization allows to essentially decrease sidelobs.

Let us consider conformal active array win N radiators. We introduce Cartesian rectangular coordinates. The electric field in the Fraunhofer region is given by expression [2, 3]

$$\vec{E}(\vec{r},t) = K/r^2 \sum_{n=1}^{N} A_n \vec{F}_n(\theta,\varphi) \exp(i\phi_n + i\omega t - ik\Delta_n), \tag{1}$$

where θ and φ are inclination and polar angels of the radius-vector $\vec{r}$, $k = 2\pi/\lambda$ – wavenumber, λ is the wavelength, K – coefficient of proportionality, $\Delta_n = x_n \sin\theta\cos\varphi + y_n \sin\theta \sin\varphi + z_n \cos\theta$ is a path-length difference, A_n, ϕ_n, $\vec{F}_n(\theta,\varphi)$ and (x_n, y_n, z_n) are the excitation amplitude (a real positive number), phase, vectorial complex direction pattern and coordinates of the respective radiating element. We have taken that excitation of all radiators depends on time as $\exp(i\omega t)$. If we take into account mutual coupling that $\vec{F}_n(\theta,\varphi)$ has to be direction pattern when the radiator is excited in the presence of the rest N-1 ones. If all elements forming respective beam have co-directional complex polarization vectors and identical phase dependence than Eq. 1 yields:

$$E(\vec{r},t) = K'/r^2 \exp(i\omega t - ikr + i\Phi(\theta,\varphi)) \times$$
$$\times\left(2\sum_{n=2}^{N}\sum_{k=1}^{n-1} A_n A_k F_n(\theta,\varphi) F_k(\theta,\varphi) \cos(\varphi_n - \varphi_k + k(\Delta_n - \Delta_k)) + \sum_{n=1}^{N} A_n^{\,2} F_n^{\,2}(\theta,\varphi)\right)^{1/2}. \tag{2}$$

Here K' is a new coefficient of proportionality, $\Phi(\theta,\varphi)$ – a phase of resulting signal, $F_n(\theta,\varphi)$ is the amplitude direction pattern – a real positive number. To obtain narrow beam directional pattern the excitation amplitudes and phases of neighboring radiators have to have small differences. In such case and if distances between neighboring radiators are less than $\lambda/2$ the sums of Eqs. 1 and 2 can be replaced by surface integrals.

The three well known consequences of Eq. 2 are:

1. Energy-flux vector $\vec{P}$ in the beam direction is maximal when $\varphi_n + k\Delta_n = const$ for all radiators. In that case $\vec{P} \sim \sum_{n=1}^{N} A_n^{\,2} F_n^{\,2}(\theta,\varphi)$.
2. Antenna gain is maximal when excitation A_n is proportional $F_n(\theta,\varphi)$ in the beam directional.
3. The sidelobes level is minimum when direction of maximal radiation of elements forming respective beam are co-directed with the beam.

As mentioned early, the sidelobes of outer beams essentially limit coverage radius. We will assume that coverage region is round. So the array shape has to be body of revolution. The second and third consequences yield that to reduce sidelobes the lateral surface radiators have to be oriented so that $\theta_n = \theta_{ob}$, where θ_{ob} is the direction of the inclination angle of the outermost beams and θ_n is the direction of maximal radiation of respective elements. A_1-A_n have to be optimized for the new radiators orientations. The detailed calculations performed by Eq. 2 yield in that case the minimum of all cells SIR increases by 1.5-4 times. In our consideration SIR means the ratio of the signal to the total interference of the all other beams.

Let us compare conformal and plane arrays. If $R >> H$ and $h, L, L_0 >> \lambda$ (L_0 is diameter of the plane array, h, L – vertical and horizontal size of conformal array) than the outermost cells size can be calculated by formulas:

$$a \approx \alpha_r R/(H/R+\alpha_r),\quad b \approx \alpha_\varphi R(H/R+\alpha_r/2)/(H/R+\alpha_r),\ \alpha_r^c = \lambda/h,\ \alpha_\varphi^c = \lambda/L,$$

$$\alpha_r^p = \sqrt{H^2/R^2 + 2\lambda/L_0} - H/R,\ \alpha_\varphi^p = \lambda/L_0,$$

$$S \approx \tfrac{\pi}{4}\alpha_r \alpha_\varphi R^2 (H/R+\alpha_r/2)/(H/R+\alpha_r)^2,\quad \frac{S^c}{S^p} \approx \frac{\alpha_r^c \alpha_\varphi^c}{\alpha_r^p \alpha_\varphi^p}\frac{H/R+\alpha_r^c/2}{H/R+\alpha_r^p/2}\left(\frac{H/R+\alpha_r^p}{H/R+\alpha_r^c}\right)^2, \tag{3}$$

where a and b are radial and cross sizes of the outermost cells, α_r and α_φ are radial and cross angles of the outermost beams. The superscripts c and p denote conformal and plane arrays.

The mass and volume of satellite and aircraft payload is limited. We will compare arrays having the same mass, volume and number of transmit-receive modules (TRM). The standard layout of the electronics modules in the active array is: the radiators is placed on the external surface of array; the TRMs is placed on the backside of the surface; also other electronic modules such as ADC/DACs, digital beam forming module, telecommunication equipment etc can be here. For conformal array these modules can be placed inside the cylindrical or elliptic surface. The radiators are on the outside of this surface. So the total volume of a plane round antenna is $V_0 = \pi L_0^2 h_0 / 4$. Eqs. 3 yield $S^c / S^p \approx H/R\sqrt{L_0/(ch_0)}$, where $c=L_0/h$ and if $h_0 > L_0 H^2/(cR^2)$ conformal array has advantages in comparison with plane array. Otherwise, characteristics of conformal array are worse. But if we take into account free space loss and transform Eqs. 3 for arbitrary values of h, L, L_0, R, H the comparison of area of different cells shows that conformal array has advantages in most cases. As an example cell distribution pattern of conformal array is plotted in Fig. 1b. The all parameters are the same as for Fig. 1a. Area of central cells in Fig. 1b is larger than in Fig. 1a. But as mentioned the potential capacity of them is essentially grater than needed.

3. Separate and dynamical apodization

Using conformal shape can reduce sidelobes of outer beams. However separate apodization (SA) allows archiving more significant result. This method can be used for plane array as well as for conformal. Usually apodization is applied as an amplitude coefficient dependent on radiator location on the antenna surface. It gives good results in decreasing sidelobes. However it increases "opposite" sidelobe for beams with big deflection angle. To avoid this effect and improve common SNR each beam should have own apodization. If array has N radiators and produces M beams then digital beam former have to transform M-elements column $[S]$ ($S_k = \exp(i\omega_k t + i\phi_k)$) of beams signals into N-elements column $[E]$ of exciting currents. It is a simple linear operation:

$$[S][F] = [E]. \tag{4}$$

$[F]$ is a constant NxM complex matrix of amplitude-phase factors, ϕ_k is a complex phase. For standard apodization this transformation has form: $[S][F'][A] = [E]$, where $[F']$ is complex matrix of phase factors, $[E]$ is a constant NxN diagonal matrix of real apodization coefficients. For receiver array the transformation has inversion form. Eq. (4) shows that SA does not need more difficult beam forming module in comparison with standard apodization. But in some cases separate apodization needs higher ADC/DAC resolution. For example ADC/DAC resolution of 34 beams array with coverage radius R=6H have to be not less then 12 bits.

The situation is more difficult for HATP, where M-55 stratospheric aircraft is used as a telecommunication platform. As the airplane cannot stay in one position and the cruising speed is about 700 km/h, the analysis show that the optimal trajectory for providing communication for a fixed region is a circle with radius 20 km. In such a case if beam directions are fixed then the cells distribution pattern will make two type of motion; firstly, the rotary motion around the center of airplane trajectory with angular velocity 10 turns per minute and secondly, translation motion along the trajectory with cruising speed. It means that the fixed handsets will change cells every 2-10 s and the handover procedures will take 10-25% of total network capacity. Moreover the quality and connection stability will be essentially less. The fixed pattern, however, solves this problem. In that case both the beams directions and beams widths have to vary with airplane moving. It can be achieves by using dynamical apodization only. The beam-forming module has to recalculate matrix $[F]$ in real time. It needs sufficiently great computation capability. The experimental development shows that using newest electronic components allows achieving sufficiently small size of digital processing system (DPS). For example the DPS size of the array having 79 radiators and producing 34 beams is about 0.5x0.5x0.35m. This system performs the following functions: DSP, beam forming, control and primary processing of signal data.

4. Smart array technology

Benefits of smart arrays are described in papers [4, 5]. However perceptible advantage can be achieved only when cells width is substantially smaller than average distance between users. Otherwise array will operate as a traditional multi beam antenna. This condition is not possible for satellite and HATP communication. Such small beam width can be satisfied by ground based array but the minimal size of 1.8 GHz antenna will be about 1.5 m and the number of RTM will be about 30 for 1-dimension and 400 for 2-dimention array. At present such antenna is very expensive. However other smart functions can be utilized for multi beam system with arbitrary beam width.

Let us consider system with wide beams and users number in cells which significantly varies with time, for example, a satellite moving over Earth surface. It produces cells that move on the Earth surface too. The population density is not constant and depends on area. For example the population density in towns and forests are essentially different. So the need of the capacity is different for different beams and depends on satellite position and time. According to the basic principles (Eqs. (2) and (3)) the beams redirection does not give any benefit. Nevertheless the beam capacity can be changed by two ways. The fist way is dynamical frequency redistribution. The antenna control module distributes frequencies to cells depending on cells needs. Of course, any frequency transfer from one cell to another can cause SIR changing for other cells. Therefore before transfer the new SIR has to be recalculated for the all other beams. This information has to be used to decide the transfer should be allowed or not. But it is a discrete operation and affects just the small number of cells. That means all the variants can be calculated over designing stage and then rules table of allowed redistribution frequencies have to be loading in the ROM of controlling module. So this method does not need extra computation. But the method gives perceptible advantage only when cells size is equal or less then overage distance between inhabited localities.

The second method lies in controlling cells position. As mentioned beam redirection does not give benefits, but a small shift of cells allow to increase capacity of the same beams up to 2-3 times. The shift distance is up to half the cell size. Let us explain this method through an example. If two towns are in one cell but adjacent cell is free the shift of them allows to separate the towns by different cells. Similarly the densely populated region can be distributed by 2-3 different cells.

The further development of smart arrays technology can lie in following method. The coverage area does not divide by cells. From control module point of view the coverage area is continuous space and the main objective is to calculate matrix of amplitude-phase factors (see Eq. (4)) so that to transmit and receive signals with desired SNR. The users do not group by cells. Each user is operated separately as it is in "narrow" beam smart array technology. But it does not mean that each user has own beam. For example, in presented method the direction pattern can be very wide and user can be in side of the diagram. This method needs development of an effective algorithm of the matrix calculation.

5. References

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