Circular Multiuser Beam-Free Phased Array Antenna for Wireless Communications and Comparison with the Standard Multisector Antennas

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Abstract

A solution for active phased array for wireless communication based on beam-free method is considered. Such antennas can be used as an alternative to the traditional multisector antennas. The multiuser beam-free method implies that coverage area is not divided into cells with different frequencies. Instead, all the users can use all the frequencies and the active array selects signals by their positions. The presented antenna has been compared with multisector antennas and multibeam phased arrays. The comparison shows that in most cases characteristics of the considered solution (SNR, SIR, directive gain, etc.) are better. Also the capacity (the maximal number of users operating on the same frequency) is equal to the number of the array elements. It is 2-4 times grater than the capacity of multibeam phased arrays or multisector antennas consisting of the same number of elements. The minimal distance between users is limited by only the signal power and noise density. If transmitter power is not limited the solution can select users at any distance.

1. Introduction

The rapid growth of the number of mobile communication users leads to the necessity to increase the communication quality and number of users that can be served simultaneously by a base station. A promising way is to use a multibeam phased array as a base station antenna. In the paper [1] the construction of multibeam phased array consisting of 3 independently operating flat panels is presented. Methods to improve characteristics of a convex phased array have been described in the paper [2]. The construction of a convex active array based on these methods has been proposed in [3]. This antenna forms on the ground surface 19 approximately round cells with equal areas. It had been shown that such antenna can provide so sharp decay of signal power that it is possible to use frequency reuse factor 1/3. In the papers [2, 3] it was mentioned that further enhancement of network capacity can be achieved by using beam-free method. This method implies that coverage area is not divided into cells with different frequencies. Instead, all the users in any part of the coverage area can use all the frequencies. In the current paper we will consider a circular adaptive array based on this method and analyze its characteristics.

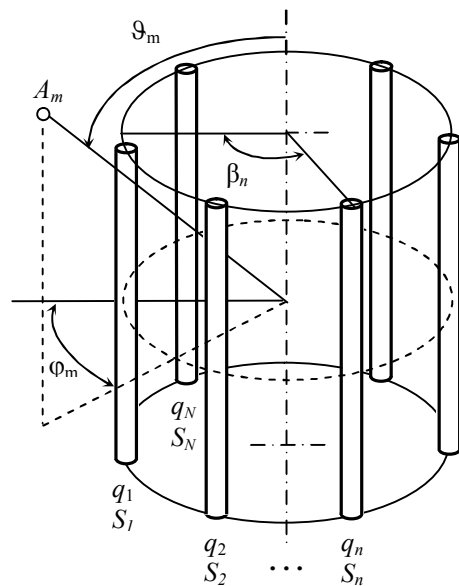## 2. Antenna Geometry and Main Formulas

Fig. 1. Antenna geometry.

Let us consider circular active phased array consisting of N elements ($\beta_n \neq \beta_i$ if $n \neq i$) placed in the same plane and M signal sources determined by their signal complex amplitudes $A_m(t)$ and complex polarization vectors $\mathbf{P}_{Am}$ (Fig. 1). The sources operate on the same frequency and are placed in the Fraunhofer zone at the angles φ_m and ϑ_m correspondingly ($\varphi_m \neq \varphi_i$ if $m \neq i$). $A_m(t) = a_m(t)\exp(j\xi_m(t))$, $a_m(t)$ are the real amplitudes, $\xi_m(t)$ are the phases, j is the imaginary unit. We assume that φ_m are known. There are many possibilities to find φ_m by the antenna itself (see, for example, [3]) and this problem is not considered in the paper.

The complex amplitude S_n of the excitation of the antenna element n is defined by the formula:

$$S_n(t) = \sum_{m=1}^{M}\Big[k_m \cdot \big(\mathbf{P}_{Am} \cdot \mathbf{P}_{Fn}^{*}(\varphi_m - \beta_n, \vartheta_m)\big)\times$$
$$\times q_n(\varphi_m - \beta_n, \vartheta_m)\cdot A_m(t)\cdot \exp(jr\cos(\varphi_m - \beta_n))\Big] , \tag{1}$$

where k_m are proportionality coefficients taking into account such constant parameters as distance between the signal sources and the

antenna, etc., $\mathbf{P}_{Fm}$ are the complex polarization vectors of the antenna elements, $\left(\mathbf{P}_{Am} \cdot \mathbf{P}_{Fn}^{*}\right)$ are the polarization transmission coefficients, q_n are the radiation patterns of the antenna elements taking into account the interaction between the other elements and structural of the antenna, $r = 2\pi R / \lambda$, R is the circle radius. We will assume that the vectors $\mathbf{P}_{Fm}$ are collinear and do not depend on the fist argument. It takes place, for example, when antenna elements are identical and have axial symmetric radiation pattern. In such case we can simplify (1):

$$S_n = \sum_{m=1}^{M} A_m(t) K_m G_n\left(\varphi_m, \vartheta_m\right). \tag{2}$$

$K_m = k_m\left(\mathbf{P}_{Am} \cdot \mathbf{P}_{Fn}^{*}\left(\varphi_m - \beta_n, \vartheta_m\right)\right)$ and does not depend on the time and number of antenna element, $G_n\left(\varphi_m, \vartheta_m\right) = $ $= q_n\left(\varphi_m - \beta_n, \vartheta_m\right)\exp\left(j r \cos\left(\varphi_m - \beta_n\right)\right)$. Further, we will usually omit the second argument in G_n meaning $G_n\left(\varphi_m\right) = G_n\left(\varphi_m, \vartheta_m\right)$.

We will require that the antenna will be able to restore exactly signals up to time independent factor i.e. to find $KA_m(t)$, where K is a constant. This requirement seems excessive but as it was shown in the paper [3] such approach results in the highest capacity in most cases. Eq. (2) shows that the exact signal restoration is feasible when $N \geq M$ and

$$rank\begin{bmatrix} G_1(\varphi_1) & ... & G_1(\varphi_M) \\ .... \\ G_N(\varphi_1) & ... & G_N(\varphi_M) \end{bmatrix} = M . \tag{3}$$

Also (2) shows that the solution will be in the linear function class i.e. A_m can be obtained as a linear combination of the element excitations: $A_m K_m = C_{m1} S_1 + C_{m2} S_2 + ... + C_{mN} S_N$, where C_{mn} are constants. It means that to analyze array characteristics (including noise parameters) we can use the standard radiation pattern technique and the considered in the paper method is applicable for transmission as well as for receiving. Therefore further we will consider the receiving antenna meaning that the transmission characteristics are the same. Notice, the combined equations (2) is always consistent due to problem formulation.

Let us consider the radiation pattern in the general linear form:
$$D(\varphi, \vartheta) = c_1 G_1(\varphi, \vartheta) + c_2 G_2(\varphi, \vartheta) + ... + c_N G_N(\varphi, \vartheta) . \tag{4}$$
If the condition (3) is true the above mentioned requirement of exact signal A_i restoration is equivalent to the condition $D(\varphi, \vartheta) = 0$ in the points $\varphi = \varphi_m$ $(m \neq i)$ and in such case $D(\varphi_i, \vartheta_i) = A_i K_i$. Of course for different i the coefficients $c_1, ..., c_N$ (and so functions $D(\varphi, \vartheta)$) are different too. We will mark the radiation patterns by subindex: $D_i(\varphi_i, \vartheta_i) = A_i K_i$. It is simple to show that in such case $D_m(\varphi, \vartheta) = C_{m1} G_1(\varphi, \vartheta) + C_{m2} G_2(\varphi, \vartheta) + ... + C_{mN} G_N(\varphi, \vartheta)$. Thus the problem of signal restoration is the problem of finding the constants C_{mn} corresponding to the above mentioned condition.

The expressions $\exp\left(j r \cos\left(\varphi - \beta_n\right)\right)$, $n = 1...N$ are linearly independent functions of argument φ. So the functions $G_n(\varphi, \vartheta)$ of argument φ are linearly independent too except special cases that we do not consider in this paper. It means that for any $\{\varphi_1, \varphi_2, ..., \varphi_{i-1}, \varphi_{i+1}, ..., \varphi_N\}$ we can always find $\{C_{i1}, C_{i2}, ..., C_{iN}\}$ so that $D_i(\varphi, \vartheta) = 0$ in these points and $\sum_{n=1}^{N}\left|c_n\right| \neq 0$. The constants C_{mn} can be calculated by the formula:
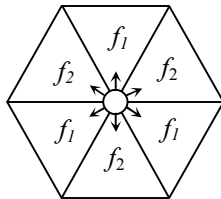

Fig. 2. The pattern of 6-sectors antenna using frequency reuse factor 1/2.

$$\begin{bmatrix} C_{i1} \\ C_{i2} \\ . \\ . \\ . \\ . \\ C_{i,N-1} \end{bmatrix} = -c_N \begin{bmatrix} G_1(\varphi_1) & G_2(\varphi_1) & ... & G_{N-1}(\varphi_1) \\ G_1(\varphi_2) & G_2(\varphi_2) & ... & G_{N-1}(\varphi_2) \\ .... \\ G_1(\varphi_{i-1}) & G_2(\varphi_{i-1}) & ... & G_{N-1}(\varphi_{i-1}) \\ G_1(\varphi_{i+1}) & G_2(\varphi_{i+1}) & ... & G_{N-1}(\varphi_{i+1}) \\ .... \\ G_1(\varphi_N) & G_2(\varphi_N) & ... & G_{N-1}(\varphi_N) \end{bmatrix}^{-1} \begin{bmatrix} G_N(\varphi_1) \\ G_N(\varphi_2) \\ ... \\ G_N(\varphi_{i-1}) \\ G_N(\varphi_{i+1}) \\ ... \\ G_N(\varphi_N) \end{bmatrix} . \tag{5}$$

The paper length does not allow to expound all the mathematical manipulations and discuss all the practically interesting characteristics. In this paper we will consider only the most specific properties and compare them with the properties of other types of antennas. The comparison with multibeam circular array is shown in Table 1. Note that the most part of the data presented in this table are rough estimation and can be used only for qualitative comparison. The exactly calculated data for the 7 elements array are presented in the next section.

Table 1. The comparison of multibeam and beam-free circular arrays.

	Multibeam array [1]	Beam-free array
Minimal number of frequency channels needed to provide continuous coverage area for 1 base station	2	1
Maximal number of users in case of using 2 frequency channels for multibeam antenna and 1 channel for beam-free antenna	$N/2$ - N [2]	N
Maximal number of users (N_f – number of frequency channels, R_f – frequency reuse factor, $R_f \leq 1$)	$\dfrac{N \cdot N_f \cdot R_f}{2}$	$N \cdot N_f$
Minimal distance between users operating at the same frequency determined by the beam (sector) width	$360°/N$	$0°$ [3]
Minimal distance between users operating at the same frequency determined by 13dB level of the signal-to-interference ratio	$180°/N$	$0°$ [3]

N is a number of array elements.

[1] according to antenna construction considered in the paper [3]

[2] depends on frequency reuse factor

[3] In theory the beam-free method can provide any required signal-to-noise ratio (SNR) for any users' position because the method assumes an exact signal restoration (i.e. the signal-to-interference ration (SIR) is equal to infinity). But Eqs. (5) and (4) yield that in the limit of small $\Delta\varphi$ ($\Delta\varphi$ is an angle between users) the directive gain is proportional to $\Delta\varphi^2$. So to provide required SNR the signal source power has to be inversely proportional to $\Delta\varphi^2$. Refer to the notes on Table 2 for the SIR and directive gain definitions used here.

3. Comparison with the Standard 6-Sector Antenna for Base Station

Let us compare a beam-free circular array with a typical 6-sector antenna using frequency reuse factor 1/2 (Fig. 2). For simplicity, we will consider the problem in a 2-dimensional formulation. The analysis of Eq. (3) shows that a beam-free equispaced array consisting of 6 elements is able to select signals not for every users' position. (The example is shown in the Fig. 3.) To avoid this problem the array has either to be not equispaced or to consist of 7 elements. We will consider the second case, the equispaced circular array consisting of 7 elements with axialsymmetric radiation patterns so that $\beta_n = 360°(n-1)/N$. The results of comparison are presented in the Table 2.
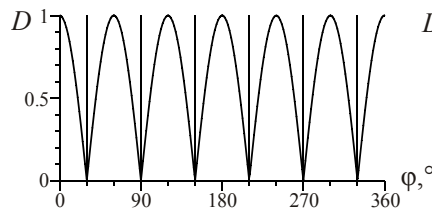

Fig. 3. The example of users' position (vertical lines) and corresponding radiation pattern when a beam-free equispaced array consisting of 6 elements with axialsymmetric radiation patterns cannot serve the users.

(If N is an even number and the antenna is equispaced the condition (3) is not true for the users' position $\varphi_m=180°/N+360°(m-1)/N$. The radiation pattern calculated by (5) and (4) is equal to zero over the all φ_m.)
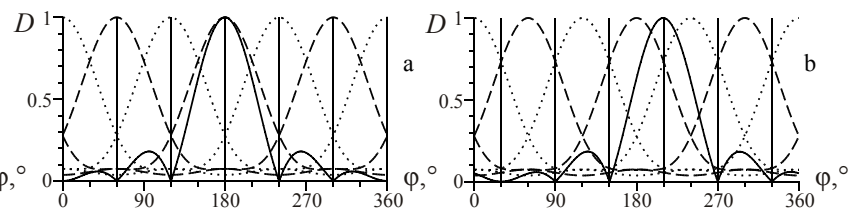
Fig. 4. Radiation patterns of a typical 6-sector antenna and the considered 7-elements array.

dash line – radiation pattern of the sectors operating at the first frequency

dot line – radiation pattern of the sectors operating at the second frequency

solid line – radiation pattern of the considered array

vertical lines – users' positions

Table 2. The comparison of the beam-free circular array consisting of 7 elements with a typical 6-sector antenna.

Number of users	7		6		6		2		2		2	
Users' position	see [1]		Fig. 4a		Fig. 4b		$\Delta\varphi = 60°$ [2]		$\Delta\varphi = 36°$ [3]		$\Delta\varphi = 20°$	
Characteristic	SIR, dB	DG, dB	SIR, dB	DG, dB	SIR, dB	DG, dB	SIR, dB	DG, dB	SIR, dB	DG, dB	SIR, dB	DG, dB
Typical 6-sector antenna (2 frequencies)	n/a	n/a	19.6	7.2	17.5	4.6	19.1	4.6	13	1.9	n/a	n/a
Beam-free array, r=3.58 [4] (1 frequency)	∞	5.8	∞	7.3	∞	6.7	∞	6.7	∞	5.9	∞	3.5
Beam-free array, r=1 [5] (1 frequency)	∞	4.7	∞	8.1	∞	8.1	∞	8.1	∞	5.7	∞	0.4

SIR is signal-to-interference ratio. $\text{SIR} = |D(\varphi_i)|^2 / \sum_{m \neq i} |D(\varphi_m)|^2$, where the summation includes all the sources operating on the frequency of wanted signal. In the case of the multisector antenna $D(\varphi)$ is a radiation pattern of the sector where user φ_i operates. In the case of the beam-free array $D(\varphi)$ means $D_i(\varphi)$. φ_i is position of wanted signal. See also the note [3] to the Table 1.

DG is the directive gain in the φ_i direction. $\text{DG}=360° |D(\varphi_i)|^2 / \int_0^{360°} |D(\varphi)|^2 \, d\varphi$; definitions for $D(\varphi)$ and φ_i are as above.

n/a means that antenna cannot serve such number or such position of users.

[1] 7 randomly placed users: φ_1=7°, φ_2=76°, φ_3=143°, φ_4=186°, φ_5=249° (wanted signal), φ_6=273°, φ_7=332°.

[2] $\Delta\varphi = 60°$ is a minimal distance between users operating at the same frequency determined for the 6-sector antenna by the sector width.

[3] $\Delta\varphi = 36°$ is a minimal distance between users operating at the same frequency determined for a typical 6-sector antenna by 13dB level of signal-to-interference ratio.

[4] r=3.58 is an optimal value calculated with the method obtained in [3].

[5] The analysis yields that if $r \leq 2$ the direction pattern of beam-free circular array weakly depends on r and so the case r=1 shows the antenna properties for small r.

4. Conclusion: the Main Properties of a Beam-Free Circular Array

1. The capacity (maximal number of users operating on the same frequency) is equal to the number of the antenna elements.
2. The comparison of antennas consisting of the same number of elements shows that the capacity of beam-free antenna is up to 2 times higher than the capacity of a standard 6-sector antenna using frequency reuse factor 1/2 and up to 3 times higher than the capacity of 3-sector antenna using frequency reuse factor 1/3.
3. The detailed comparison with the 6-sector antenna shows that in the most cases such characteristics of the beam-free array as SNR, SIR, directive gain, etc., are higher.
4. Theoretically in case of the beam-free array the minimal distance between the users operating on the same frequency is equal to 0. Practically this distance is limited by the maximal transmitter power. In any case for the same transmitter power this parameter is significantly smaller for the beam-free array than for the multisector antenna.
5. Beam-free array is easily flexible. To increase the capacity it is just sufficient to add the antenna elements without construction changing.
6. The presented antenna increases capacity of CDMA, TDMA and OFDMA networks as well as FDMA.
7. The beam-free method needs special procedure to determine users' position and more precision amplitude-phase manipulations.

5. Acknowledgments

6. References

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2. I. Yu. Sergeev, Yu. S. Ushakov and E. I. Demidenko, "Using Conformal Shape, Separate and Dynamical Apodization to Improve Characteristics of Multibeam Active Phased Array", *Proceedings of 2010 Asia-Pacific Radio Science Conference*, Toyama, Japan, September 22-26, 2010.
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