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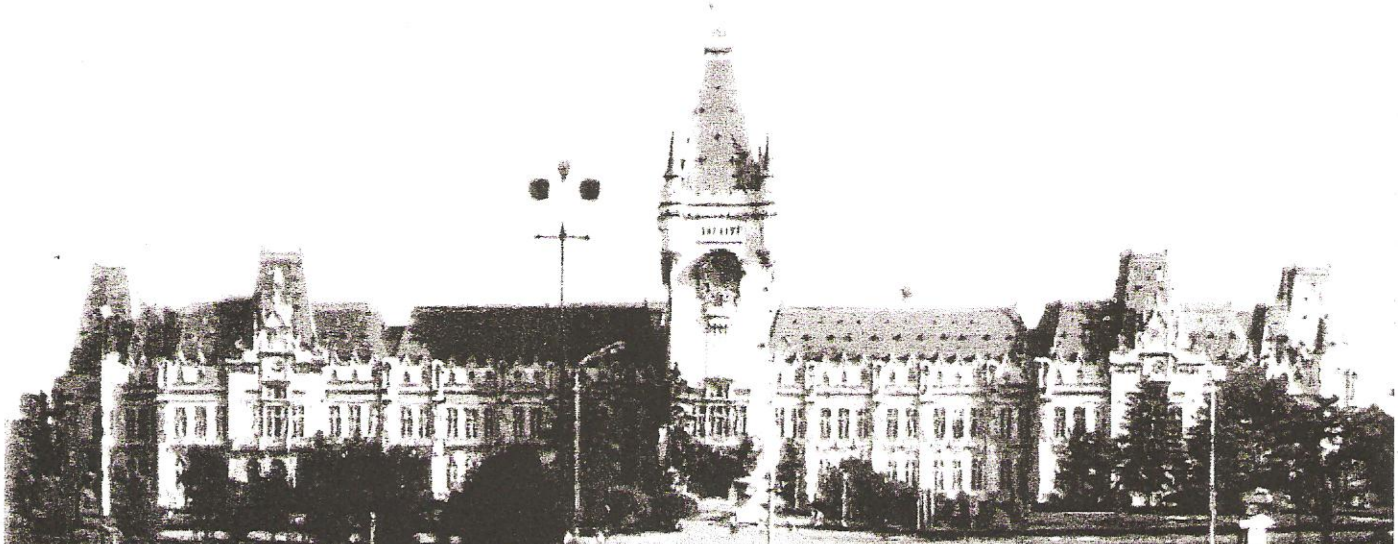

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ANALYSIS OF CIRCULAR ARRAYS AS SMART ANTENNAS FOR CELLULAR NETWORKS

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ABSTRACT

Smart antennas are considered vital components of the future 3G mobile communication networks [1], [2], [3]. The topic is very broad in nature and includes adaptation algorithms [4], [5], receiver architecture, channel modeling and estimation, adaptive coding, antenna theory [6], [7], [8] etc. This paper is a study of circular array applications as smart antennas intended to evaluate the advantages and the drawbacks and to establish guidelines to design its parameters. A classification of smart antennas is also included.

1. INTRODUCTION

Base station antennas in conventional cellular networks are either omnidirectional or sectorized. This configurations lead to a waste of transmitting power and to increased interference levels because most of the transmitted power is radiated in other directions than the one where the intended user is. As a result only a small fraction of the total transmitted power is usefully captured by the desired user, the rest of it acting as interference power for other users in the cell. In the same time the base station receives interference power from all the active users in the cell (or sector). Smart antennas transmit to (or receive from) a small angular sector around the desired direction enabling both a more efficient power transmission and smaller interference levels.

A smart antenna consists of an N element antenna array **and** an associated powerful signal processing block. The output signals from (or to) each of the antenna elements are individually and adaptively processed taking into account the inherent spatial information they contain (or the necessary spatial information to be included). In most of the actual implementations the signals from (or to) the antenna elements are multiplied with complex weighting coefficients. For an appropriate (adaptive) choice of the weighting coefficients the radiation diagram of the antenna array has a narrow main lobe towards the desired user **and** nulls towards (hopefully) all the interfering directions. One can see that not the antenna array itself is "smart", but rather the complete antenna system including the signal processing block. This weight adaptation is the smart part and more exactly a smart antenna array should be called an adaptive antenna [1].

The main objective achieved by using smart antennas is the increase of network capacity as each base station is able to serve more users due to the more selective spatial transmitting and receiving of its antenna. In the same time the quality of service (QoS) is improved: the number of blocked and dropped calls is smaller as a result of the better transmission quality due both to increasing the desired signal power and reducing the interference power. Other beneficial results include a possible reduction of the delay spread, allowing higher data rates, and a reduction of the transmission power in both uplink and downlink [2].

We will present in the following a classification of smart antennas, an analysis of circular antenna arrays and, finally, the benefits of using them as smart antennas in cellular networks.

2. SMART ANTENNA CLASSIFICATION

Smart antennas can be divided into four classes: switched beam arrays, spatial filtering arrays, space-time processing units, and space-time detection blocks [5].

The *switched beam* arrays are connected to the tranceiver through a RF-beamforming unit. This one uses predefined sets of weighting coefficients allowing the main lobe of the radiation pattern to take (usually) evenly distributed discrete directions in space. The selection of the main direction of radiation is based on the maximum received signal power or the minimum bit error rate [5] [8]. The received signal is further processed by a standard receiver. The main feature of this technique is its simplicity. Because the main lobe and the radiation pattern nulls can take only predefined discrete directions the improvement brought by switched beam arrays strongly depends on the relative positions of the active users.

The other three classes of smart antennas use separate receivers for each antenna element, the received signals are converted to baseband, sampled and digitally processed to derive the optimal values for the weighting coefficients. These values are then used to multiply the signals received by the individual antennas before summing them up. Thus the main lobe and the nulls of the array radiation pattern can be put virtually into any direction in space.

If the signals received by the individual antennas have small time dispersion, there is no need for an equalizer and the antenna array acts as *spatial filter*. If an equalizer is needed the antenna array filters the received signal (jointly or successively) both in space and time and it is called a *space-time processing* unit. When equalization and signal detection are made simultaneously the antenna array is called a *space-time detection* unit. The latter implementation offers the best performance, but also it is the most complex.

Smart antennas can operate as a diversity antenna or as a beamforming array. Diversity relies upon the statistical independence of the individually received signals, thus having a very small probability that all of them be simultaneously in a deep fading. By using advanced combining methods for the diversity signals, the signa-to-noise+interference ratio (SNIR) can be maximized [6], [7]. The beamforming technique relies on the close proximity of antenna elements and, as a result, on the

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high correlations between the signals they receive. This allows forming an array radiation pattern that both enhances the desired signal and suppresses the interference.

3. CIRCULAR ARRAY ANALYSIS

Most of the simulation results and practical implementations found in the literature refer to linear or planar arrays [6], [7], [8]. Linear array of dipoles are extensively used in the present cellular networks and their extension to adaptively controlled arrays is quite a straightforward process. Also, two linear arrays on orthogonal directions could approximate very well a planar array [9]. Also, most important, simulation and practical results show they have very useful radiation patterns and require moderate complex control systems and algorithms.

Linear arrays have the main drawback of symmetric array factor around the element supporting line meaning that the radiation in two opposite directions can not be independently controlled. In order to obtain this necessary feature one has to block the radiation in the undesired direction by special means (metallic reflectors, usually). Both linear arrays with reflector and planar arrays have the disadvantage that their main lobe can be moved only in half of the space. Finally, for beam tilting mechanical means should be used or an extra control feature should be implemented.

The radiation pattern of circular arrays inherently covers the entire space, could be quasi omnidirectional or directive (Fig. 1) and, in the latter case, the main lobe could be oriented in any desired direction. Moreover, beam tilting is naturally obtained through the same type of control used for the lobe orientation.

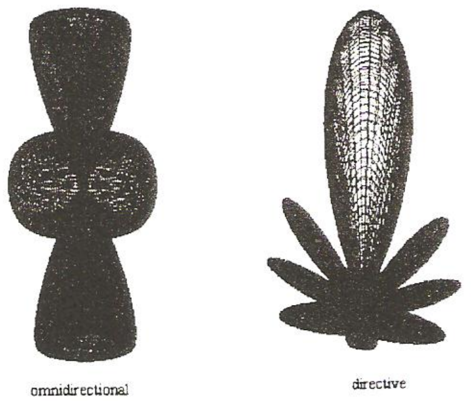

Figure 1. Possible shapes of a circular array pattern

For the design of circular array one has to adequately choose the number of antennas in the array, their position on the circle, and the circle radius. Also, the control function of the complex weighting coefficients should be specified in order to obtain the desired radiation pattern. In order to establish some design guidelines a study of the radiation pattern in the circle plane is made in the following.

An $N = 8$ element array equally spaced on an $a/\lambda = 1$ relative radius circle is arbitrarily chosen (Fig. 1), where λ is the wavelength of the radiated frequency. For uniform space coverage obviously the antennas should be uniformly distributed on the circumference and their transmitting power should be the same. Thus, the position of the antenna m is unambiguously by the angle:

$$v_m = m\frac{2\pi}{N}, \quad m = 1, \ldots, N \tag{1}$$

its corresponding radius makes with the positive direction of the axis Ox. Also, the modulus of all of the weighting coefficients is chosen as one. For the main lobe to point in the (θ_0, ϕ_0) direction, the phase of the weighting coefficients should be [9]:

$$\delta_m = -2\pi\frac{a}{\lambda}\sin(\theta_0)\cos(\phi_0 - v_m), \quad m = 1, \ldots, N \tag{2}$$

Fig. 2 shows the array normalized radiation pattern in the circle plane for $(\theta_0, \phi_0) = (\pi/2, 0)$ and $(\theta_0, \phi_0) = (\pi/2, \pi/3)$ and reveals that the radiation pattern shape changes when the main lobe changes its direction. This phenomenon would induce uncontrollable CINR levels in a cellular mobile system as the interference attenuation depends on the continuous changing relative positions of the interferers and the desired user.

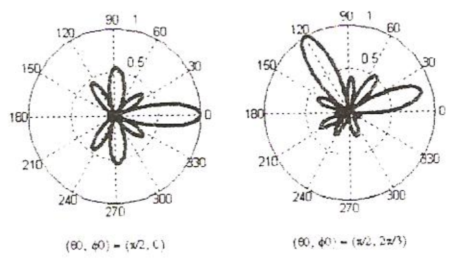

Figure 2. Array radiation pattern for two directions of the main lobe

In order to evaluate the influence of this phenomenon on the array parameters the relative level of the greatest secondary lobe of the radiatation pattern was computed for every possible orientation of the main lobe in the circle plane. The results presented in Fig. 3 show a periodic variation with minimal levels of the secondary lobe when the main lobe orientation is aligned with the position of an antenna element in the array and with maximal values for main lobe directions in between the above ones. The dynamic range of variation is about 2 dB. For arrays with an increased number of elements (Fig. 4) this periodic variation of the secondary lobe level remains, but the dynamic range and the average level decreases with N. One concludes from these figures that at least $N = 13$ antennas are needed in the array should its parameters remain almost unchanged when the main lobe direction changes.

This condition is quite severe taking into account the circumference length values for UMTS (≅ 86 cm) or even GSM (≅ 2 m) networks: if antenna elements are separated less than $\lambda/2$ from each other their properties greatly differs from those in free space due to mutual influences. As a result the overall characteristics of the array are unpredictable.

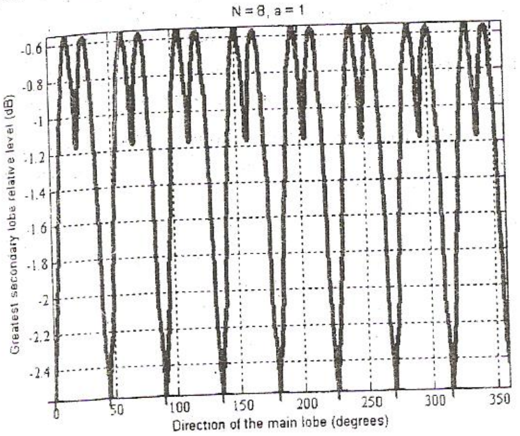

Figure 3. Relative level of the greatest secondary lobe vs. direction of the main lobe for $N = 8$.

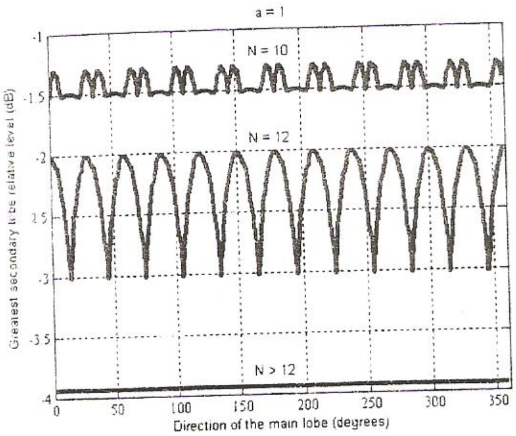

Figure 4. Relative level of the greatest secondary lobe vs. direction of the main lobe for $N = 10$, 12, and $N > 12$.

Next, the influence of the circle radius is investigated and three smaller than λ values are taken into account. Also, a range of 3 to 16 for the number of antennas is considered. The results are synthetically presented in Table 1. One can see that for smaller values of the radius the minimum number of required antennas is smaller and this is an advantage for practical implementations, as both the size and the weight of the array become smaller. Moreover, the array efficiency increases for smaller radius values as the level of the greatest secondary lobe decreases. For $a = 0.25\lambda$ even a 5 element circular array has convenient levels for the greatest secondary level.

Another parameter that greatly influences the array capability of improving the SNIR value is the main lobe beam with. Simulations showed that its value is not influenced by the number of antenna elements in the array, but only by the circle radius. As expected, the main lobe becomes broader as the circle radius decreases.

Table 1. Dynamic range of the greatest secondary lobe relative level (dB) vs. circle radius

N	$a/\lambda = 1$		$a/\lambda = 0.5$		$a/\lambda = 0.25$	
	max	min	max	min	max	min
3	-0.00	-0.32	-0.00	-1.09	-1.28	-2.29
4	-0.00	-0.71	-0.00	-2.91	-2.18	-5.98
5	-0.39	-1.28	-1.12	-1.33	-4.93	-5.17
6	-0.00	-0.41	-1.10	-3.38	-4.77	-5.58
7	-1.69	-2.30	-3.94	-3.95	-5.17	-5.17
8	-0.55	-2.57	-3.88	-3.98	-5.15	-5.19
9	-1.77	-2.24	-3.95	-3.95	-5.17	-5.17
10	-1.30	-1.52	-3.95	-3.95	-5.17	-5.17
11	-2.19	-2.29	-3.95	-3.95	-5.17	-5.17
12	-2.02	-3.02	-3.95	-3.95	-5.17	-5.17
13	-3.94	-3.94	-3.95	-3.95	-5.17	-5.17
14	-3.94	-3.94	-3.95	-3.95	-5.17	-5.17
15	-3.94	-3.94	-3.95	-3.95	-5.17	-5.17
16	-3.94	-3.94	-3.95	-3.95	-5.17	-5.17

Table 2. Main lobe 3 dB beamwidth (degrees)

N	$a/\lambda = 1$	$a/\lambda = 0.75$	$a/\lambda = 0.5$	$a/\lambda = 0.25$
3...16	24	30	44	88

It appears that one has to trade off the secondary lobe level for main lobe beamwidth: a narrow main lobe pattern should be used if one expects more interferers around the desired user and a small secondary lobe level should be favored in opposite situations.

4. APPLICATION IN A CELLULAR NETWORK

An N element circular array is used as base station antennas in cellular network with identical hexagonal cells and a 7-cell cluster. A user with randomly generated position is activated in every cell of a cluster. Mobile antennas are considered as omnidirectional and transmitting the same power. Path loss is computed as a power (-3.5) of distance and a lognormal shadowing noise with 6.5 dB standard deviation is superimposed. The SNIR for the central cell base station is evaluated and averaged over 1000 iterations. Comparison is made with the SNIR values for the same operational conditions, but with base station omnidirectional antennas.

There are considered two kind of radiation pattern control: switched beam and completely adaptive. In the first case a number of 16 evenly distributed discrete positions for the main lobe are considered in order to keep the antenna gain closed to its maximum for the worst positions of the desired user (in the middle of two successive main lobe discrete position) even for the smallest beam with (24 degrees).

Table 3. Improvement due to the switched beam (dB)

N	$a/\lambda = 1$		$a/\lambda = 0.75$		$a/\lambda = 0.5$		$a/\lambda = 0.25$	
	av.	st.dev.	av.	st. dev.	av.	st.dev.	av.	st.dev.
3	0.09	*0.28*	0.04	*0.22*	0.20	*0.16*	0.34	*0.20*
4	0.30	*0.17*	0.15	*0.20*	0.22	*0.19*	0.37	*0.28*
5	0.10	*0.20*	0.31	*0.13*	0.24	*0.21*	0.33	*0.13*
6	0.28	*0.18*	0.32	*0.22*	0.29	*0.28*	0.27	*0.19*
7	0.22	*0.30*	0.29	*0.17*	0.31	*0.34*	0.39	*0.15*
8	0.29	*0.19*	0.38	*0.19*	0.37	*0.2[illegible]*	0.28	*0.27*
9	0.37	*0.18*	0.42	*0.29*	0.33	*0.22*	0.32	*0.29*
10	0.16	*0.24*	0.37	*0.24*	0.22	*0.38*	0.30	*0.18*
11	0.28	*0.31*	0.51	*0.21*	0.46	*0.14*	0.29	*0.20*
12	0.22	*0.23*	0.21	*0.27*	0.33	*0.23*	0.31	*0.13*
13	0.28	*0.16*	0.35	*0.27*	0.35	*0.21*	0.27	*0.30*
14	0.21	*0.28*	0.28	*0.23*	0.31	*0.34*	0.26	*0.28*
15	0.34	*0.34*	0.35	*0.22*	0.46	*0.26*	0.20	*0.39*
16	0.27	*0.31*	0.31	*0.18*	0.25	*0.30*	0.13	*0.29*

As Table 3 reveals the improvement brought by the switched beam control is too small to be considered as a real improvement: less than 1 dB for all combinations of circle radius and number of antennas. These disappointing results could be explained by the mutual relation beamwidth and secondary lobe level. For uniformly distributed users the interferers are equally favored by a too broad main lobe or a two great secondary level, while the desired user is clearly disadvantaged by the discrete-only orientation of the main lobe.

Table 4. Improvement due to the adaptive control (dB)

N	$a/\lambda = 0.25$		$a/\lambda = 0.5$		$a/\lambda = 0.75$		$a/\lambda = 1$	
	av.	st.dev.	av.	st. dev.	av.	st.dev.	av.	st.dev.
3	2.87	*0.58*	3.27	*1.11*	3.05	*0.67*	2.94	*0.71*
4	4.48	*1.41*	3.54	*0.94*	2.30	*0.62*	4.60	*0.94*
5	3.58	*0.51*	4.36	*1.39*	3.57	*0.43*	3.78	*0.95*
6	4.52	*0.63*	4.93	*1.79*	4.71	*0.45*	4.33	*0.70*
7	4.85	*0.72*	4.01	*0.69*	5.59	*0.70*	4.14	*1.29*
8	6.04	*1.32*	4.37	*0.73*	5.50	*0.67*	3.87	*1.18*
9	5.06	*0.78*	4.53	*1.10*	5.24	*0.7[illegible]*	4.29	*0.68*
10	4.67	*0.64*	6.59	*1.21*	5.48	*0.85*	4.32	*0.53*
11	5.29	*0.65*	6.24	*0.88*	5.61	*0.76*	4.15	*0.91*
12	6.08	*1.16*	6.39	*0.54*	6.14	*1.90*	4.25	*0.95*
13	6.54	*0.82*	6.25	*1.09*	5.46	*0.94*	4.25	*0.46*
14	6.74	*0.44*	6.98	*0.83*	5.83	*0.68*	4.67	*0.86*
15	6.88	*0.88*	6.48	*0.91*	5.24	*1.47*	4.61	*0.93*
16	6.69	*0.89*	6.16	*0.88*	5.72	*1.25*	3.94	*0.89*

The use of an adaptive control offers a clear improvement (more than 4 dB) as compared to the omnidirectional case. The results are better for smaller circle radius and slightly vary with the number of antennas as soon as it is great enough. This suggests that for a perfect main lobe orientation towards the desired user its beamwidth is less important than the secondary lobe level.

The simulation results reveal that a circular array could be used as a smart antenna in a cellular network only if a completely adaptive control is implemented.

The gain induced by the circular shape of the array could be enhanced by an appropriate choice of the element antenna type. This choice is very important also for the vertical pattern control, which is not influenced by the circular shape of a horizontal plane array. This aspect is out of scope of the present paper and it will be addressed to in future works.

5. SUMMARY

Circular arrays applications as smart antennas in cellular networks were investigated. It was shown by simulations that the gain in terms of improved carrier to interference ratio is better than 4 dB and that a careful choice of the element antenna could help in increasing performance.

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