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Pattern Synthesis with Uniform Circular Arrays for the Reduction of WCDMA Intercell Interference

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Abstract

The deployment of advanced antenna arrays at the base stations of cellular systems is a key technique in reducing intercell interference, and thus increasing the number of served users. Uniform circular arrays (UCAs) provide 360 degrees of coverage, their patterns are steering-invariant and their sidelobe levels are controllable. This paper investigates the use of UCAs having specially synthesized patterns at the base stations of WCDMA cellular systems. The decrease in the ratio of intercell interference to intracell power resulting from the use of these arrays in a beam-steering scheme will be assessed, and the advantages and disadvantages of each pattern type will be discussed. The paper also looks into the interference reduction obtained by stacking several UCAs to form a cylindrical array.

Key Words: *Antenna arrays, WCDMA, intercell interference.*

1. Introduction

Increased interference in the downlink of 3G WCDMA cellular networks is cardinal in limiting the number of served users [1]. To reduce interference, advanced antennas are used [2], and adaptive beamforming is employed to increase cell coverage and user capacity through antenna gain and interference rejection [3]. Two beamforming methods are normally considered: the fixed beam, and the steered beam. The first makes use of a specified number of fixed beams to cover a cell sector, whereas the second allows pointing the beam towards a specific user.

In the beam steering case, the antenna pattern needs to remain unaltered irrespective of the look direction. This was an assumption in [4], but with the use of uniform circular arrays, as was done in [5], this property can be obtained. In [5] UCAs with Chebyshev patterns were designed, using a technique first proposed in [6]. UCAs, where *uniform* means *equi-spaced*, are very practical for deployment at base stations since they provide all-azimuth, i.e. 360 degrees, coverage.

The technique of [6] is used to transform the UCA into a virtual uniform linear array (ULA). Interesting UCA patterns are obtained by applying a special excitation to this virtual ULA, and then transforming it back into a UCA. The transformation guarantees the steering-invariance property of the resulting UCA pattern, whereas the choice of the ULA excitation is responsible for the sidelobe level control and the directivity of the pattern. Three excitation types that result in controllable sidelobe levels are the famous Dolph-Chebyshev, the modified-Chebyshev [7], and the discretized Taylor One-Parameter [8] excitations. The first two result in *equi*-ripple sidelobes, and the third in decaying sidelobes. A Dolph-Chebyshev distribution gives the lowest sidelobe level for a desired beamwidth, or the smallest beamwidth for a prescribed sidelobe level. The modified-Chebyshev distribution results in a slightly larger beamwidth but also in a smaller number of sidelobes and solves the directivity saturation problem of Chebyshev distribution for high numbers of elements. Because it ensures a decaying behavior of the sidelobes, a Taylor One-Parameter distribution is most practical for use. Decaying sidelobes lead to less noise and interference from the far-out sidelobes, as compared to the other two distributions. Patterns synthesized using the Taylor One-Parameter distribution are the most directive and have a beamwidth smaller than that of modified-Chebyshev but still larger than conventional Chebyshev. A uniform distribution is a special case of the Taylor One-Parameter distribution, but applying a uniform excitation to the ULA is not suitable when sidelobe level control is a priority.

The patterns of the obtained UCAs, which will be respectively denoted the Chebyshev, modified-Chebyshev and Taylor UCAs, are steering-invariant with controllable sidelobe levels. Using these arrays at the base stations of WCDMA cellular systems in a beam-steering scenario leads to substantial decrease in the ratio of intercell interference to intracell power, as compared to the omnidirectional or the 3-sector cases. In the omnidirectional case, there is one sector per cell and the base station (BS) is installed at the center of the cell and equipped with an omnidirectional antenna. In the 3-sector case, three antennas are used at the BS, each covering 120 azimuthal degrees [9].

A stack formed by a number of co-centered UCAs is called a cylindrical array. Cylindrical antenna arrays have high directivities, narrow beams, and low sidelobe levels. In [10], it was shown that the use of cylindrical arrays as smart antennas leads to more increase in user capacity in the downlink of WCDMA systems when compared to linear and circular arrays of comparable dimensions and same number of elements. The high directivities of cylindrical arrays lead to an increase of interference in the adjacent cells, whereas their narrow beams and low sidelobes help efficiently in interference mitigation. Thus, it would be interesting to study intercell interference when cylindrical arrays are deployed at the base stations, and compare the results to those obtained with circular arrays.

This paper investigates the Chebyshev, modified-Chebyshev and Taylor UCA types, compares them, and assesses their effect on interference reduction. Among them, the Taylor UCAs result in the smallest ratio of intercell interference to intracell power, followed in order by Chebyshev and modified-Chebyshev UCAs. The paper also looks into the interference reduction performance of uniform cylindrical arrays (UCylAs). This paper is organized as follows. In Section 2, the problem is formulated, the transformation used in the pattern synthesis is explained, and formulas for the different excitations used are given. In Section 3, numerical examples are given to compare the proposed UCAs and UCylAs, the simulation model is set up, and the intercell interference results are given. Finally, concluding remarks are given in Section 4.

2. Problem Formulation

In a WCDMA cellular system, the interference caused by non-orthogonal codes being used in other cells is called intercell or co-channel interference. The ratio of intercell interference to received intracell power is given as [9]

$$F_{k,l} = \frac{\sum\limits_{j=1,j\neq l}^{J} P_{T,j} g_{k,j}}{P_{T,l} g_{k,l}} \tag{1}$$

where l denotes the mobile station (MS) of interest, k denotes the serving BS, P_T is the total BS transmit power, and J is the number of cell sectors in the network. In (1), $g_{k,j}$ is expressed as

$$g_{k,j} = K\left(d_{kj}\right)^{-n} \xi_{kj} G_{kj}, \tag{2}$$

where K is the path gain, n is the pathloss exponent, d_{kj} is the distance from BS k to MS j, G_{kj} is the antenna gain from BS k in the direction of MS j, and ξ_{kj} is the lognormal shadowing from BS k to MS j. ξ_{kj} is a zero-mean Gaussian random variable with variance σ^2.

For a UCA with N isotropic elements and radius r, let $\mathbf{a}_c(\theta)$ denote its array response vector. Let $\mathbf{a}_v(\theta)$ be the array response vector of the corresponding virtual ULA. $\mathbf{a}_v(\theta)$ is given by [6]

$$\mathbf{a}_v(\theta) = \mathbf{J}(N,\lambda,r)\ \mathbf{F}(N,h)\ \mathbf{a}_c(\theta) \approx \left[e^{-jh\theta},\ldots,1,\ldots,e^{jh\theta}\right]^T. \tag{3}$$

In (3), θ is the azimuth angle,

$$\mathbf{J}(N,\lambda,r) = \operatorname{diag}\left\{\left(j^m\sqrt{N}J_m\left(2\pi r/\lambda\right)\right)^{-1}\right\}, m = -h,\ldots,0,\ldots,h, \tag{4}$$

and

$$\mathbf{F}(N,h) = \frac{1}{\sqrt{N}}\begin{bmatrix} 1 & \omega^{-h} & \omega^{-2h} & \cdots & \omega^{-(N-1)h} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & \omega^{-1} & \omega^{-2} & \cdots & \omega^{-(N-1)} \\ 1 & 1 & 1 & \cdots & 1 \\ 1 & \omega^{1} & \omega^{2} & \cdots & \omega^{(N-1)} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & \omega^{h} & \omega^{2h} & \cdots & \omega^{(N-1)h} \end{bmatrix}. \tag{5}$$

In (4), $J_m(\cdot)$ is the Bessel function of the first kind and order m, λ is the wavelength; and in (5), $\omega = e^{j2\pi/N}$. The size of the virtual ULA is $N_v = 2h+1$, and h is given by

$$h = \max\left\{h \,\middle|\, h \leq \frac{N-1}{2} \text{ and } \frac{J_{h-N}(2\pi r/\lambda)}{J_h(2\pi r/\lambda)} < \varepsilon\right\} \tag{6}$$

for some predetermined ε. The approximation in (3) requires that $N \gg 2\pi r/\lambda$.

It follows from (3) that

$$\mathbf{C}^T(\theta_s,h)\ \mathbf{a}_v(\theta) = \mathbf{C}^T(\theta_s,h)\,\mathbf{J}(N,\lambda,r)\ \mathbf{F}(N,h)\ \mathbf{a}_c(\theta) \tag{7}$$

where θ_s is the steering angle and $\mathbf{C}$ is a $(2h+1)$-element vector given by

$$\mathbf{C}(\theta_s,h) = \left[I_{-h}e^{jh\theta_s},\ \cdots\ I_{-1}e^{j\theta_s},\ I_0,\ I_1e^{-j\theta_s},\ \cdots\ I_he^{-jh\theta_s}\right]^T, \tag{8}$$

and $\mathbf{I}_v = \left[\begin{array}{cccccc} I_{-h}, & \cdots & I_{-1}, & I_0, & I_1, & \cdots & I_h \end{array} \right]$ is the coefficients vector of the virtual ULA. From (7), it is deduced that the coefficients vector of the UCA is

$$\mathbf{D} = \mathbf{C}^T \ \mathbf{J} \ \mathbf{F}. \tag{9}$$

Equation (9) was derived when the array elements are isotropic but also holds for the case of non-isotropic elements. A method described in [11] makes it easy to account for mutual coupling in the formulation.

For a modified Chebyshev UCA with a sidelobe level ratio equal to R, the coefficients of the virtual linear array have mirror symmetry and are given by

$$I_m = \frac{1}{N_v} + \frac{2}{N_v \ R} \sum_{t=1}^{h} \cos\frac{2mt\pi}{N_v} \left[T_{2h/q}\left(\gamma \cos\frac{t\pi}{N_v}\right)\right]^q, \tag{10}$$

where $N_v = 2h + 1$ is the number of elements of the virtual array, $-h \leq m \leq h$, $T_p(\cdot)$ denotes a Chebyshev polynomial of order p, q is an integer greater than unity, and $\gamma = \cosh\left[q \cosh^{-1}\left(R^{1/q}\right)/2h\right]$. The linear array becomes a conventional Dolph-Chebyshev array when $q = 1$. A binomial array is the special case of the Dolph-Chebyshev array when R goes to infinity (no side lobes).

For the Taylor UCA case, the elements of the virtual ULA should have the following coefficients [8, 11]

$$I_m = \mathrm{I}_0\left[\beta\left(1 - [m/h)]^2\right)^{1/2}\right] \tag{11}$$

where $\mathrm{I}_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind, and β is a parameter that controls the maximal sidelobe level (MSLL). When $\beta = 0$, the coefficients will be equal, leading to a uniform excitation and a MSLL of about –13 dB.

Cylindrical arrays are a subclass of the hybrid linear and circular arrays. Pattern synthesis with cylindrical arrays was treated in [12], where patterns with high directivities, narrow beams, and low sidelobes were synthesized. The array factor of a cylindrical array is the product of the array factor of a linear array by that of a circular array. Hence, the pattern synthesis for cylindrical arrays reduces to two separate pattern synthesis tasks: the synthesis of a circular array and the synthesis of a vertical linear array. Each of the UCAs forming the UCylA can be of the three types discussed above. However, in most cases, all UCA stacks are of the same type, and their relative excitation is selected according to a certain distribution, that of a linear array. So it could be a uniform, Chebyshev, modified Chebyshev, or a Taylor distribution.

3. Simulation Results

To check the steering-invariance property of the three UCA types, we take as a first example a UCA with $N = 35$, MSSL = –20 dB, and an inter-element spacing $d = 0.194\lambda$. The radius $r = d/\left(2\sin\left(\pi/N\right)\right) = 1.084\lambda$. For $\varepsilon = 0.05$, $h = 16$ so the virtual linear array has 33 elements. The in-plane azimuth array pattern of the modified-Chebyshev with $q = 2$ and Taylor UCAs are plotted in Figures 1 and 2, respectively, for $\theta_s = -90^\circ$, 0°, and 60°.

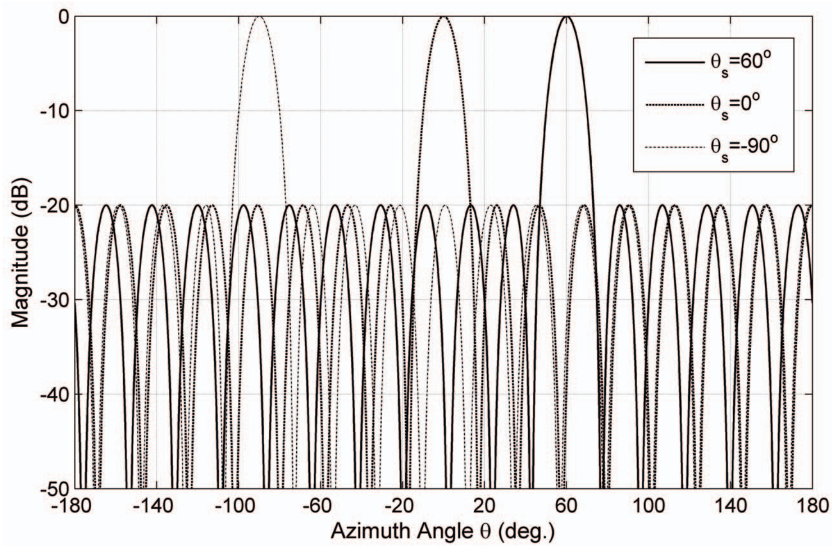

Figure 1. Normalized array patterns in the azimuth plane for the modified Chebyshev UCA for $N = 35$, MSSL = –20 dB, and $d = 0.194\lambda$.

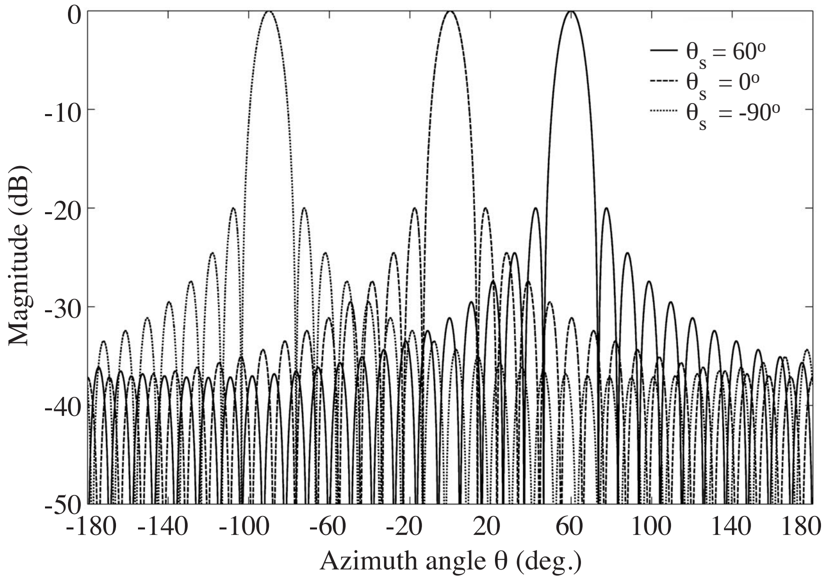

Figure 2. Normalized array patterns in the azimuth plane for the Taylor UCA for $N = 35$, MSSL = –20 dB, and $d = 0.194\lambda$.

As can be seen, the three patterns in each case are the same except for the angle shift. In the Taylor UCA case, $\beta = 2.222$, which is independent of the steered direction. This steering-invariance property is also enjoyed by Chebyshev UCAs, which are a special case of the modified-Chebyshev UCAs.

A second example is taken to contrast the three UCA types. Here, N is 39, MSLL = –20 dB, $r = \lambda/2$, and $\theta_s = 0°$. For $\varepsilon = 0.05$, the virtual linear array has 37 elements ($h = 18$). Figure 3 depicts the in-plane azimuth array patterns of Chebyshev, modified-Chebyshev ($q = 2$) and Taylor UCAs.

The Taylor UCA has a narrower main lobe compared to the modified-Chebyshev design, but still a wider one compared to the Dolph-Chebyshev design. The modified-Chebyshev UCA has the smallest number of sidelobes. The maximum-to-minimum absolute coefficient ratio (dynamic range of the taper weights) is smallest for the Taylor UCA, followed respectively by that of the modified-Chebyshev and Chebyshev cases. The same comparison holds for the maximum phase difference in the coefficients. This property leads to a simpler feed network design for the Taylor UCA case.

A simulation model based on a symmetric network of equivalently equipped BSs is adopted to assess the decrease in the intercell interference to intracell power ratio. The simulated network consists of 7 hexagonal cells, as shown in Figure 4.

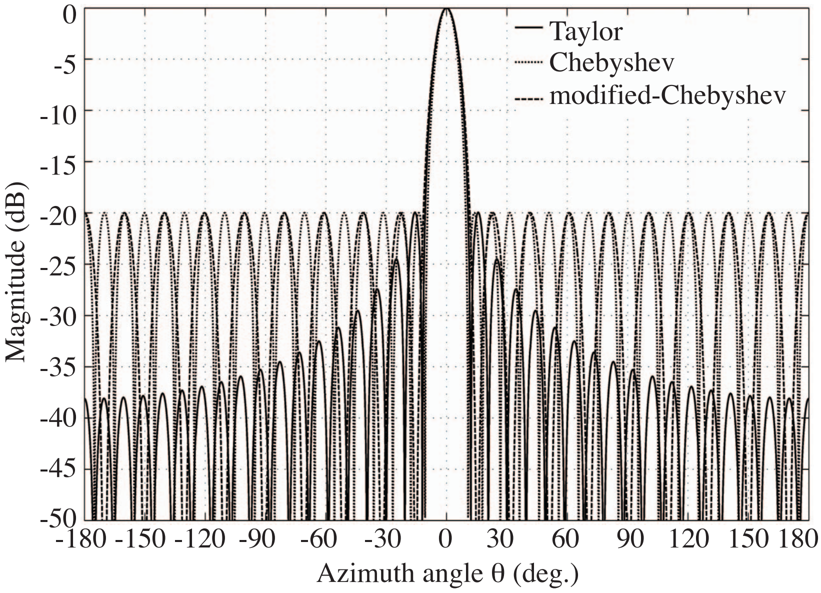

Figure 3. Patterns for $N = 39$, MSSL = –20 dB, $r = \lambda/2$, and $\theta_s = 0°$.

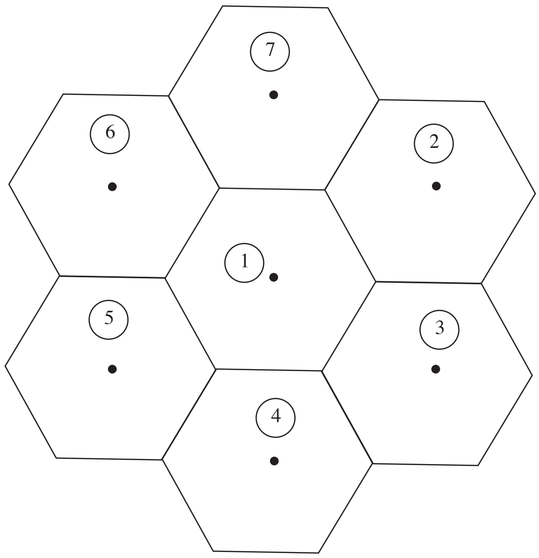

Figure 4. Simulated Network.

The MSs are assumed uniformly distributed over the network and present only in the azimuth plane, and the BSs are assumed to transmit at their maximum power. The UCA assumed at each BS has 33 elements and a MSLL of –20 dB. The elements are considered isotropic and mutual coupling disregarded.

Suitable antenna elements can be used though, and the Matrix Pencil method can be employed to compensate for the mutual coupling effects. Fast fading is considered averaged out by perfect power control, diversity, and channel coding. In the simulation, $K = -50$ dB, $\sigma = 8$ dB, and the pathloss exponent n is varied from 2 to 5, which is the interval of practical values appearing in empirical measurements [13]. 10000 independent iterations were taken, where in each a user is created at a random location and the ratio of intercell interference to received intracell power, as given by (1), is computed for this user. Finally, the average value of F taken over all iterations is calculated. The resulting average value of F for the Dolph-Chebyshev, modified-Chebyshev and Taylor designs compared to each others and to the omnidirectional case is plotted in Figure 5 versus n. Evidently, the use of beam steering with the three UCA types results in much lower F in comparison with the omnidirectional case, and this is due to the narrow beam and low sidelobes in the patterns of the UCAs. As expected, F decreases with increasing n. A larger n means more power attenuation, and consequently less interference with other users. The Taylor UCA results in the smallest F. This is again a virtue of the decaying sidelobe pattern which incurs less interference from the direction of the sidelobes. The narrower beam of the Chebyshev UCA, as compared to its modified-Chebyshev counterpart, leads to a smaller F.

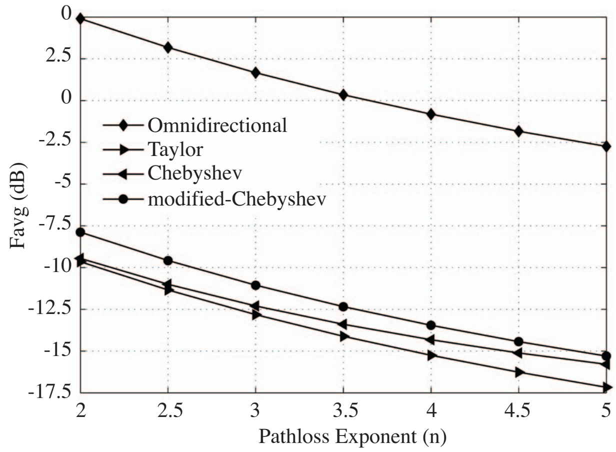

Figure 5. Average F versus pathloss exponent n.

To investigate the interference reduction performance of a UCylA, a cylindrical array consisting of 3 UCAs with $kr = 10$ and 33 elements in each stack is considered. Each of the UCAs is of Taylor type with MSLL = –20 dB. The distribution on the 3-element linear array in the vertical direction is a Chebyshev distribution with 20 dB SLL and optimal element spacing (i.e. leading to the narrowest main beam). The performance of this cylindrical array is compared to that of a 99-element Chebyshev UCA with the same radius and SLL = –20 dB, and also to the 3-sector case. The results are reported in Table 1.

Table 1. Simulation Results Comparing F_{avg} of UCylA with Chebyshev UCA and 3-Sector Cases.

	3-Sector case	Chebyshev UCA	UCylA with Taylor UCA and Chebyshev ULA
Directivity(dB)	8.22	5.4	13.98
F_{avg}	0.92	0.023	0.109

It is shown that this cylindrical array was outperformed by the Chebyshev UCA in terms of interference reduction. The same result holds when the UCA is of modified Chebyshev or Taylor types, or when the linear array distribution in the UCylA is a uniform, a modified Chebyshev, or a Taylor distribution.

4. Conclusion

To meet the growing number of 3G WCDMA subscribers, capacity enhancement and the reduction of intercell interference in WCDMA systems is a necessity. Deploying advanced antenna array at the base stations, combined with the use of adaptive beamforming is a key technique used in this respect. Uniform circular arrays provide 360 degrees of coverage in the azimuthal plane, and as a result they fit well in this scenario. This paper presented three types of UCAs whose patterns are independent of the steering angle and their sidelobe level is controllable. The Chebyshev, modified-Chebyshev and Taylor UCAs were obtained by first transforming the UCA into a virtual uniform linear array (ULA) and then applying Chebyshev, modified-Chebyshev or discretized Taylor One-Parameter excitation to the virtual ULA, which is transformed back into a UCA. Employing these arrays at the base stations of WCDMA cellular systems leads to significant decrease in the ratio of intercell interference to intracell power, compared to the case of the cell being served by an omnidirectional antenna. The Taylor UCAs lead to the smallest ratio of intercell interference to intracell power, are also the most directive for large number of array elements, and are the most practical for use. This is due to the decaying sidelobes in their pattern. The Chebyshev UCAs always have the narrowest beam, whereas the modified-Chebyshev UCAs generate the least number of sidelobes but have the broadest beam and result in the highest ratio of intercell interference to intracell power.

A stack of co-centered UCAs is a cylindrical array characterized by a high directivity, a narrow beamwidth, and a low SLL. In previous work, cylindrical arrays were proved robust in increasing the user capacity in the downlink of WCDMA systems. In that respect, they outperformed linear and circular arrays of comparable dimensions and same number of elements. In this paper, however, cylindrical arrays did not match UCAs in terms of interference reduction, although their interference rejection is still very good compared to the omnidirectional and the 3-sector cases. Thus, they can be employed whenever a compromise between user capacity (directivity) and interference reduction is sought.

References

[1] H. Holma, A. Toskala, WCDMA for UMTS, Wiley, 2000.

[2] J. S. Blogh, L. Hanzo, Third Generation Systems for Intelligent Wireless Networking: Smart Antennas and Adaptive Modulation, Wiley, 2002.

[3] J. Litva, T. Lo, Digital Beamforming in Wireless Communications, Artech House, 1996.

[4] E. Yaacoub, R. Kaissi, Z. Dawy, "Chebyshev antenna arrays for WCDMA downlink capacity enhancement", IEEE PIMRC 2005, Berlin, September 2005.

[5] B. K. Lau, Y. H. Leung, "A Dolph-Chebyshev approach to the synthesis of array patterns for uniform circular arrays," IEEE International Symposium on Circuits and Systems, Geneva, Switzerland, May 28-31 2000.

[6] D. E. N. Davies, "A transformation between the phasing techniques required for linear and circular aerial arrays," Proc. IEE, Vol. 112, No. 11, pp. 2041-2045, Nov. 1965.

[7] A. Safaai-Jazi, "Modified chebyshev arrays," Proc. IEE, Vol. 145, No. 1, pp. 45-48, Feb. 1998.

[8] C. A. Balanis, Antenna Theory, Wiley-Interscience, 2005.

[9] K. Hiltunen, R. De Bernardi, “WCDMA downlink capacity estimation”, IEEE Vehicular Technology Conference (VTC), Tokyo, May 2000.

[10] E. Yaacoub, K. Kabalan, A. El-Hajj, A. Chehab, “Cylindrical antenna arrays for WCDMA downlink capacity enhancement,” IEEE ICC 2006, Istanbul, June 2006.

[11] K. Y. Kabalan, A. El-Hajj, M. Al-Husseini, “The Bessel planar arrays,” Radio Science, Vol. 39, No. 1, RS1005, Jan. 2004.M.

[12] E. Yaacoub, M. Al-Husseini, A. Chehab, K. Kabalan, A. El-Hajj, “Pattern synthesis with cylindrical arrays”, World Scientific and Engineering Academy and Society (WSEAS) Transactions on Communications, Vol. 5, No. 12, pp. 2198-2207, December 2006.

[13] A. Goldsmith, Wireless Communications, Cambridge University Press, 2005.