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Flat-Top Ring-Shaped Cell Design for High-Altitude Platform Communications

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Abstract — In this paper, a new design for ring-shaped cells is introduced where to improve the power distribution and carrier-to-interference ratio (CIR) over the cell area. The designed cell has flat-top radiation pattern with minimal ripples in the service area while the out-of-cell area has lower radiation levels. The new design utilizes two weighting functions applied to a vertical linear array; the first is responsible for the flat-top design and the second smoothes the pattern and reduces the sidelobe levels. The resulted power pattern has a uniform distribution over the cell stripe with as small as 0.25 dB ripples and a uniform CIR values greater than 43 dB within the cells which reduces the burden of power control and increases the immunity to propagation problems.

Index Terms — High altitude platforms, directional antennas, phased antenna arrays, mobile radio communications

I. INTRODUCTION

Wireless mobile communications services with higher data rates have gained an increased demand which need to develop more innovative communications infrastructures. Terrestrial systems and satellite systems are the well-established existing technologies providing mobile communication both have their own advantages and disadvantages. The low-cost, low-power user terminals, short propagation delays and higher capacity are the main advantages of terrestrial systems, while it suffer from the multipath-fading and high scattering of radio signals. In addition, to provide higher system capacity, it should have a large number of base stations creating many other problems such as site acquisition and complex infrastructure. On the other hand, satellite systems provide reduced infrastructure and better radio coverage especially at higher elevation angles; however it suffer from the long delay especially for the geo-stationary satellites, higher launch costs and complexity in constellation for the low-earth orbit satellites. Recently, an innovative communication technology based on high-altitude platforms (HAPs) has gained attention as it preserves many advantages of both terrestrial and satellite systems but also provide special advantages of their own [1-3].

These platforms are positioned at altitudes 17–22 km high and have the potential to deliver broadband services cost effectively. A single HAP with communications payloads onboard can replace a large number of terrestrial base stations and their backhaul infrastructure. The high-altitude property of HAPs indicates good radio coverage and line-of-sight communications as in satellite systems but with lower propagation delays comparable to that of terrestrial systems. HAPs are considered nowadays as a substantial part of the future integrated terrestrial/satellite networks for providing wireless communication services [1]. In addition, HAPs may be used in other applications such as disaster monitoring and mitigation [4] and global positioning [5].

An important parameter that affects the HAP system performance is the type of antennas used to provide the radio coverage especially for the cellular systems. The multi-beam horn (MBH) antenna and antenna arrays were developed for high-speed transmission at 48/47-GHz in [6], while in [7], a low sidelobe level and asymmetric beam antenna was developed using lens antenna to provide almost circular footprint especially at lower elevation angles. In [8], the concentric ring array (CRA) is examined to provide an improved HAP cellular coverage performance where it has many advantages such as independent azimuth beamforming and lower sidelobe levels. The capability of shaping the cells to optimize the system performance is not an easy task in both conventional terrestrial and satellite systems where varying the cell area faces some difficulties in rearranging the new cells and reallocation of channels for each cell as well as outlining the desired cell boundary due to the variations in the propagation conditions. In terrestrial systems the main shaping of the cells was in sectorizing the beams to improve the CIR or to extend the coverage of the cell in one direction as in highway coverage, while in satellite systems, the shaping of cells is possible; however, the resulted cells suffer from its very large area and consequently reducing the system capacity. The HAPs will close the gap between the capability of smartly shaping the cells and the required smaller cell area to provide both the improvement in system performance and the desired higher capacity.

On the other hand, HAP stations suffer from some of the positional instabilities especially the rotational motion of the platform [4], where the platform can rotate around its vertical access and cause severe problems in the

coverage. Therefore some researches [9-10] have been dealt with this problem and introduced the ring-shaped clustering as in [9] where this new shaped cells can be formed by multi-beam antenna arrays and these beams are rotated by a suitable rate to form these cells. In [11] the method has been modified to include vertical arrays instead of two-dimensional arrays as in [9] and this actually reduced and simplified the processing techniques. The generated ring cells in [11] are designed to improve the coverage in terms of the carrier-to-interference ratio (CIR) based on reducing the sidelobe levels by the conventional windows techniques.

However, the power is not uniformly distributed within the cell resulting in variable CIR, therefore in this paper we propose a technique to both improve the CIR and also provide in-cell uniform received power and uniform CIR.

The paper is arranged as follows; section II demonstrates the ring-cell clustering and geometry and section III introduces the technique of vertical arrays. Section IV describes the proposed beamforming technique. Section V discusses the resulted power distribution and sidelobe levels both within the cell and at the other outer areas and Section VI provides the effect of the proposed technique on the CIR and its distribution and the coverage ratio. Finally Section VII concludes the paper.

II. RING-CELL CLUSTERING AND GEOMETRY

A schematic diagram of a HAP system employing the ring-shaped cells is shown in Fig. 1. Each ring is characterized by its central radius and width and all ring cells created by a specific platform are concentric. The cells can be controlled by the antenna array on board the platform. As shown in Fig. 2 the ring has an inner, central, and outer radii of r_1, r, and r_2 respectively and the ring width is w_r. These parameters are related to each other as

$$r_1 = r - \frac{w_r}{2} \tag{1}$$

$$r_2 = r + \frac{w_r}{2} \tag{2}$$

$$r = h\,tan\,\theta_o \tag{3}$$

where h is the platform altitude and the beam pointing angle is θ_o.

The ring-cell boundaries are controlled by the beam that forms the cell and in other words, the width of the cell is controlled by the beamwidth BW_θ as shown in Fig. 2. Therefore one can design any ring-cell by utilizing a suitable array configuration with appropriate beamforming technique.
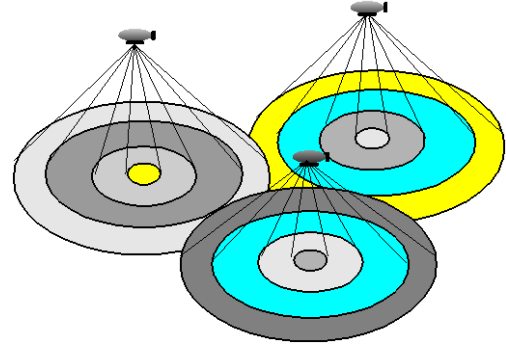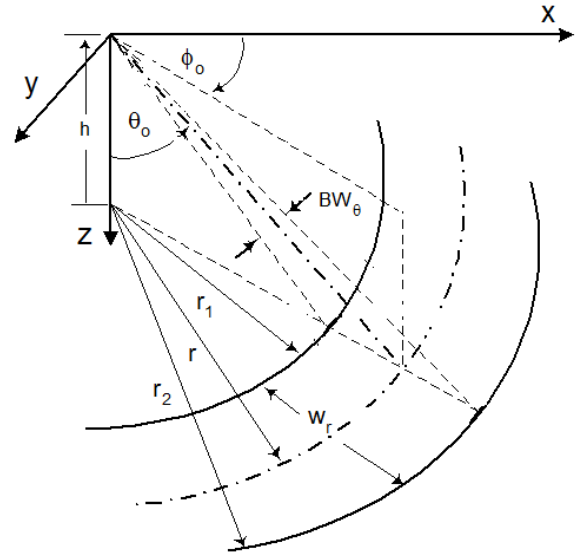

Figure 1: Ring-shaped cells for HAPs

Figure 2: Geometry of a ring-shaped cell

In addition, the power distribution in the cell interior depends on the beamforming technique applied to the array and the power radiated outside the cell must be lowered also to reduce the interference from other cells.

A geometrical manipulation to Fig. 2 shows that the ring-cell width w_r is given by:

$$w_r = 2h\left(\frac{tan\left(\frac{BW_\theta}{2}\right)}{cos^2\,\theta_o - sin^2\,\theta_o\,tan^2\left(\frac{BW_\theta}{2}\right)}\right) \tag{4}$$

Another important parameter of the ring-shaped cell is its area. The ring area A_r is given by:

$$A_r = 4\pi h^2\left(\frac{tan\,\theta_o\,tan\left(\frac{BW_\theta}{2}\right)}{cos^2\,\theta_o - sin^2\,\theta_o\,tan^2\left(\frac{BW_\theta}{2}\right)}\right) \tag{5}$$

which is used in cellular system design. Controlling A_r is also dependent on the type of array used for cell generation along with the applied beamforming technique. In the next section, the vertical linear array is

demonstrated as the array configuration used for ring-shaped cell generation.

III. VERTICAL ARRAYS FOR RING-CELL CLUSTERING

The idea of vertical array is very simple. It is just a linear one-dimensional uniform array that has elements arranged vertically on the z-axis as shown in Fig. 3.

The array gain can be given by the following equation:

$$G\left(\theta\right) = \sum_{n=1}^{N} w(n)^{*} \, e^{\left(j2\pi\frac{d}{\lambda}(n-1)\cos(\theta_o)\right)} \qquad (6)$$

Where $w(n)$ is the weighting value of the nth element, d is the interelement spacing, λ is the wavelength of the carrier signal and θ_o is the main lobe direction measured from the positive z-axis. The radiation pattern this array is independent on the azimuth angle ϕ and therefore has symmetrical pattern around the vertical z-axis as shown in Fig. 4 for a linear array of 10 elements fed uniformly and has the main lobe directed towards 30 degrees.

This important property gives the capability of forming ring-shaped cells on the ground if these beams are directed towards ground from HAP. The cell boundary actually may be defined between the 3-dB contours.

Due to the symmetry in the radiation pattern it can be drawn with θ only to simplify the pattern and make it more readable. The power pattern can be further improved in the sidelobe regions by using suitable tapering technique but the power distributed between the 3-dB contours is still non-uniform as shown in Fig. 5 where the peak power is approximately at the center between the cell boundaries and falls down at the edges. This varying power will result in variable carrier-to-interference ratio which affects the quality of service. Therefore if we design a flat-top power pattern for this cell, it is expected that the power control will be relaxed and the distribution of the carrier-to-interference ratio within the cell will be improved as well.
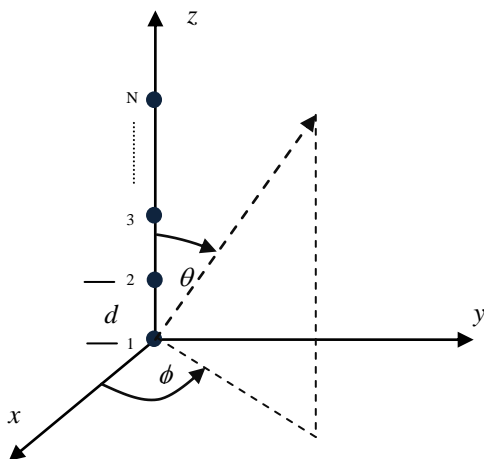

Figure 3: Uniform linear vertical array

IV. FLAT-TOP BEAM SYNTHESIS TECHNIQUE RELATED WORKS

In this section we propose a weighting function $w(n)$ that is composed of two parts; the first is $w_{FT}(n)$ which is responsible for the flat-top design and the second is $w_{AT}(n)$ which is an amplitude tapering function used for sidelobe reduction or:

$$w(n) = w_{FT}(n) \, w_{AT}(n) \qquad (7)$$

The flat-top amplitude function is proposed to be a *sinc* function which is well-known in the frequency spectrum of the time pulse. An analogy is made here for the angular spectrum which is needed to be pulsed therefore we adjust the *sinc* function in the amplitude weighting and introduce some phase shift to steer the beam into the desired direction. The amplitude weighting function can be expressed as:

$$w_{FT}(n) = \frac{sin\left(\tau\left(n-\frac{N+1}{2}\right)\right)}{\tau\left(n-\frac{N+1}{2}\right)} e^{j\pi\,(n-1)\cos(\vartheta_o)}, \qquad (8)$$

Where τ is the required ring width in radians, N is the number of elements in the array, n refers to the nth element and ϑ_o is the direction of main lobe forming the ring cell.

The other part is proposed to be:

$$w_{AT}(n) = cos\left(\frac{\pi\alpha\left(n-\frac{N+1}{2}\right)}{N}\right) \qquad (9)$$

Where α is denoted by the rolling factor which controls the tapering window profile and is limited by the following inequality:

$$0 \leq \alpha \leq 1 \qquad (10)$$

Fig. 4 demonstrates the profile of $w_{AT}(n)$ with the array elements at different values of α. Increasing the value of α will make the curve more deep.

On the other hand, the flat-top weighting function $w_{FT}(n)$ varies basically with the ring width τ and the total number of elements. This variation is depicted in Fig. 5 where the total number of elements is normalized and the ring width is kept at 10 degrees.

Decreasing the ring width will broaden $w_{FT}(n)$ as shown in Fig. 5 at the same number of elements. The combined weighting function $w(n)$ can be therefore demonstrated as shown in Fig. 6 at $\tau = 10^o$ and $\alpha = 1$. The effect of multiplication especially at values of α close to 1 will smooth the truncation of $w_{FT}(n)$ and hence improves the angular spectrum especially the sidelobe levels.

V. POWER PATTERN AND SIDELOBE LEVELS

The effect of weights in (7) on the power pattern can be demonstrated in Fig. 7. In this figure, an array of 200

elements is weighted so that the beam is directed towards 30° and the beamwidth is nearly 10°. The rolling factor is arbitrary chosen as unity for maximum *sinc* smoothing. The power distributed in the 3dB region of the beam is depicted in Fig. 8 where some minor ripples result due to the limited number of the array and the truncation of the *sinc* function. These ripples can be reduced by the tapering function $w_{AT}(n)$ which eliminates the sudden changes in $w_{FT}(n)$ especially at α close to unity. On the other hand, the tapered $w_{FT}(n)$ will result in broaden beam so that the resulted beamwidth will be greater than the required one and this may require some increase in the number of elements or deigning the array with a lower value of τ.

Regarding sidelobe levels, both $w_{FT}(n)$ and $w_{AT}(n)$ has the tapering effect on the amplitude weighting, therefore the sidelobe levels will be greatly reduced as shown in Fig. 7 which is lower than 40 dB from the main lobe level.

A close view on the 3dB region of the beam in shown in Fig. 8 where there are small ripples of approximately 0.25 dB magnitude. These ripples result from the truncation of $w_{FT}(n)$ and the limited number of the array elements. The effect of the tapering function $w_{AT}(n)$ on this region is also to reduce these ripples. Another remark from this figure is the rapid changing edge at the 3dB points which indicates lower radiated power outside the cell.

VI. DISTRIBUTION OF CARRIER-TO-INTERFERENCE RATIO (CIR) FOR FLAT-TOP RING CELLS

In this section, the carrier-to-interference ratio (CIR) for the flat-top ring cells is examined and compared with the conventional beams. First we define the CIR for the HAP system as:
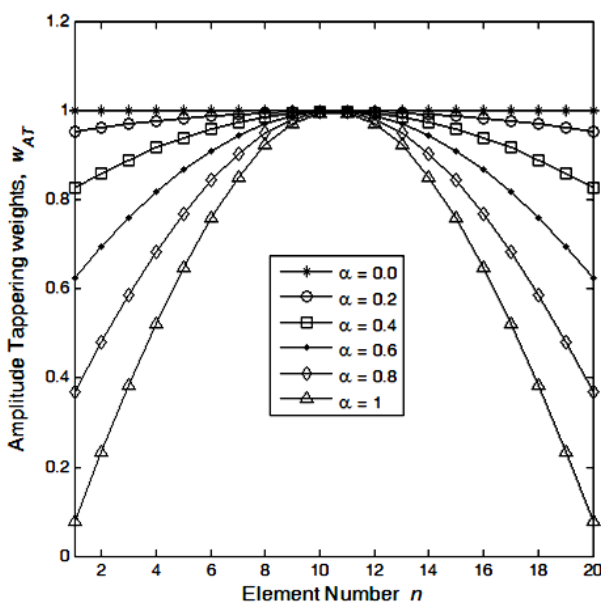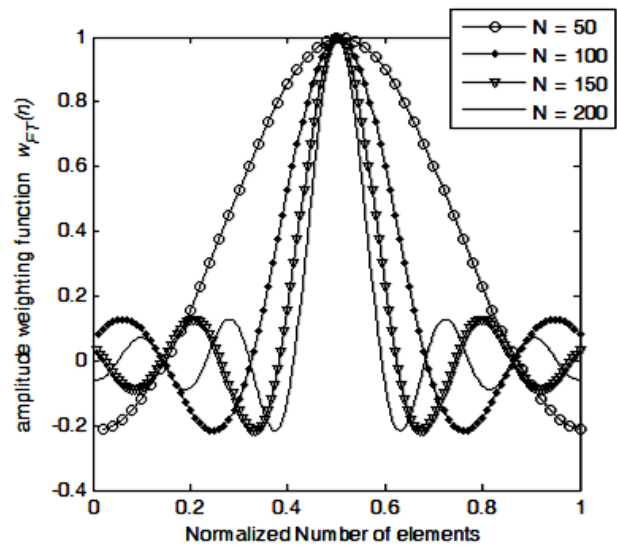

Figure 5: Amplitude weighting function at different values of the total number of elements and $\tau = 10^{o}$
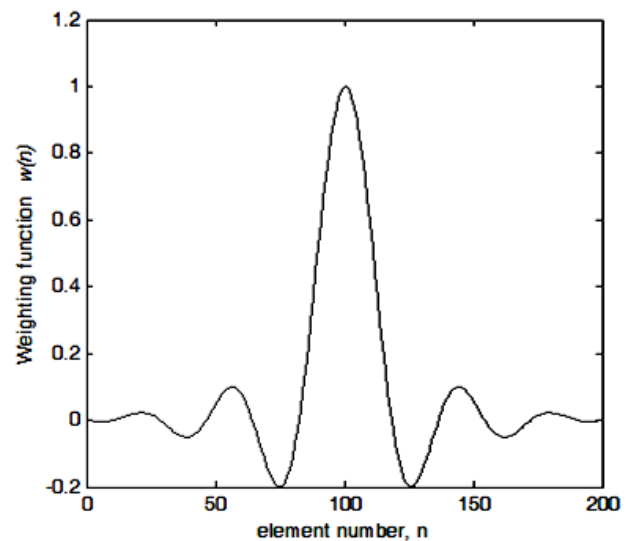
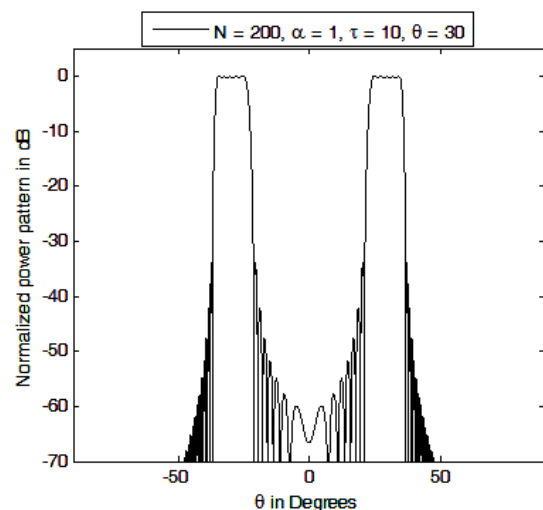Figure 6: Array amplitude weights at $N = 200$, $\tau = 10^{o}$ and $\alpha = 1$.

Figure 4: Amplitude tapering window at different values of the rolling factor.

Figure 7: Array normalized power pattern for a beam directed at 30° and width of 10° generated by 200 element linear array with $\alpha = 1$.

$$CIR = \frac{C}{\sum_{k=1}^{K} I_k} \qquad (11)$$

Where C is the desired carrier power and I_k is the kth co-channel interference power from K interfering cells.

As a case study, assume a ring cellular system of 5 co-channel cells as shown in Fig. 9 where the cluster size is formed by two rings so we have two different groups of cells repeated outwardly.
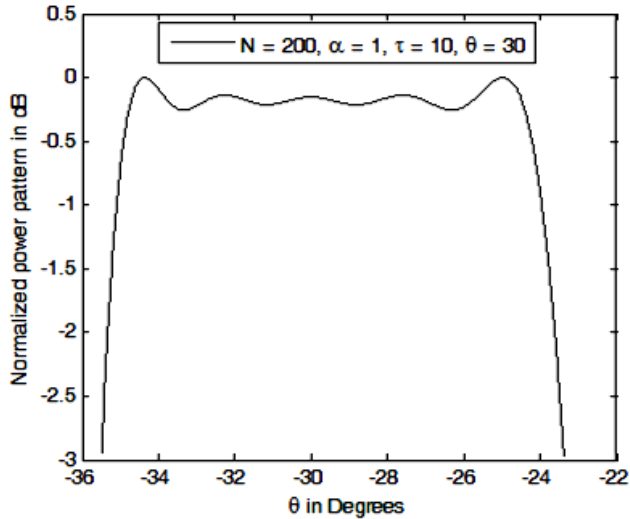
Figure 8: The normalized power distribution within the coverage area of the ring showing some ripples of 0.2dB.

These cells are formed using 200 elements vertical array with multibeams directed towards (17 29 39 46 52) degrees respectively and of average beamwidth of 5 degrees and the value of α is 1. The relative power pattern is clipped at 3dB to focus on the distributed power within the cells. The HAP is located at 20 km high and this will give an outermost ring radius of about 25 km with average ring width of 2.5 km.

As depicted in this figure the illuminated power will be almost uniform over the ring width for all rings as expected. Fig. 10 shows the relative illuminated power over the entire area clipped at -60 dB where the power falls greatly beyond the outermost ring. On the other hand Fig. 11 depicts the CIR variation for this system where the reduced sidelobe levels results in a large CIR values that can reach theoretically to 80 dB at some regions in the cell. A useful representation for the distribution of the CIR within the cells is the coverage ratio shown in Fig. 12. In this Fig., the cell will be covered 100% with CIR greater than 43 dB and the curve falls rapidly towards 20% for areas covered with CIR greater than 60 dB. Falling rapidly means to a large extent uniform CIR distribution within the cell which reduces the burden of power control and improves the quality of service. Also the higher values of CIR mitigate the expected degradation in propagation conditions.

To ensure the uniform CIR variation within the cells, a close view for a sample ring will be shown as depicted in Fig. 13 for the second ring. In this figure, the contours are spaced 1 dB apart and study is repeated in Fig. 14 for a separation of 0.5 dB and both figures does not indicate

any contours within the cell boundary which means almost uniform CIR distribution within the cell.
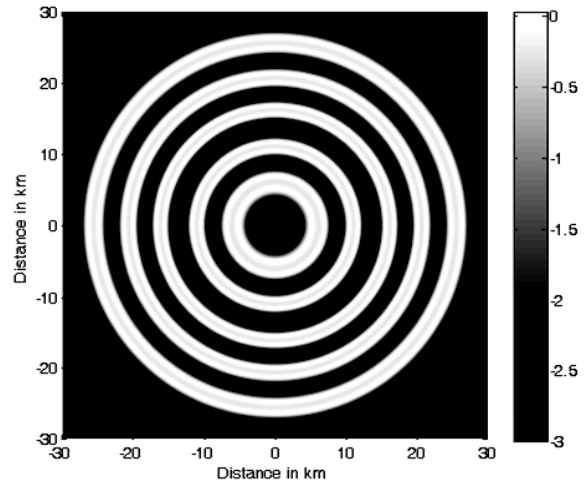
Figure 9: Relative power illumination for 5 rings of average width of 5° clipped at 3dB.
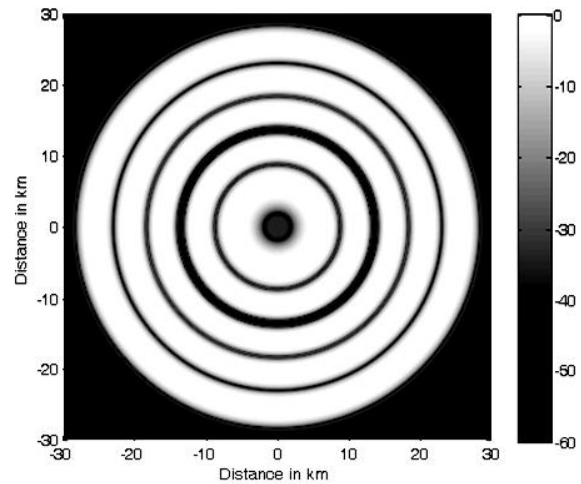
Figure 10: Relative power illumination for 5 rings of average width of 5° clipped at 60dB.
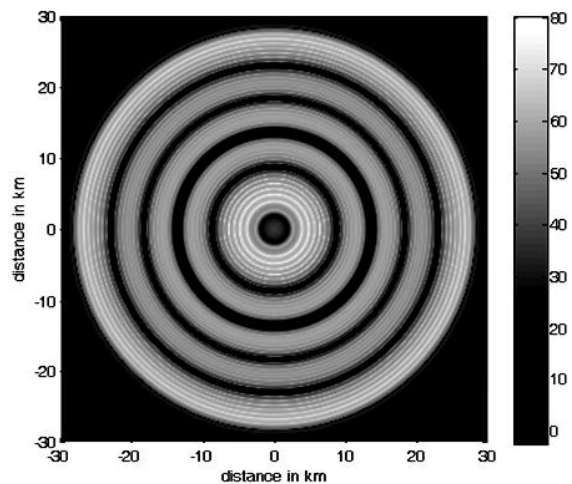
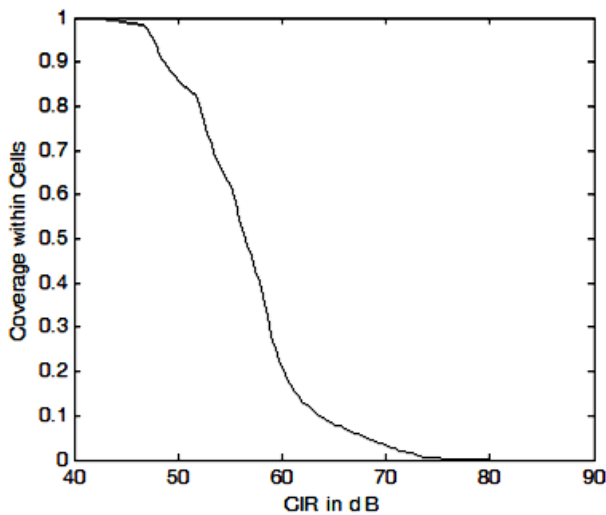Figure 11: CIR variation for a cluster size of 2.

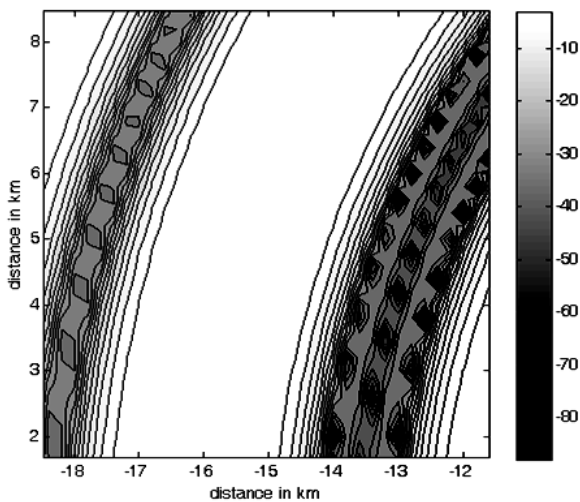Figure 12: Coverage ratio within the ring cells.

Figure 13: Relative variation of CIR in dB for a portion of the second inner ring with contours spaced 1dB.
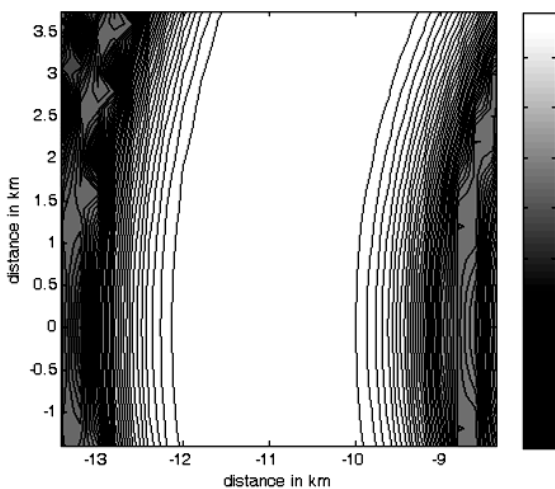

Figure 14: Relative variation of CIR in dB for a portion of the second inner ring with contours spaced 0.5dB.

VII. CONCLUSIONS

In this paper, the beam shape of the ring cells has been improved utilizing a new composite weighting function comprised by two subfunctions; the first flatten the power pattern over the cell stripe and the other reduces the in-cell ripples and sidelobe levels. The analysis of this technique shows that a uniform power pattern with a lower in-cell ripple of less than 0.25 dB can be obtained and this will reduce the power control needed for the roll of the conventional beam shapes towards the cell boundaries. As a consequence of the improved power pattern, the CIR has been improved both in value and distribution within the serving ring cells and this will increase the immunity to the propagation problems in cellular systems.

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