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DESIGN OF HIGH ALTITUDE PLATFORMS CELLULAR COMMUNICATIONS

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Abstract—Cellular communications using high altitude platforms (HAPs) will predominate the existing conventional terrestrial or satellite systems but requires some optimization especially in the cellular radio coverage design. The design of HAPs cellular system suffers from increasing cell area when directing the same beam to cover lower elevation regions and therefore requires some modification in its location. In this paper either spot-beam antennas or antenna phased arrays are used in the radio coverage which are optimized in directing their beams to satisfy mostly uniform cellular layout with minimal coverage problems such as coverage gaps between cells or excessive cells overlap. The cells locations determination is done through proposed algorithm that takes into consideration the cell area increase at lower elevation angles and provides mostly uniform radio coverage especially at the cell edges.

1. INTRODUCTION

High altitude platforms (HAPs) has been developed wherein a large scale airship is positioned at a predetermined altitude approximately 20 km high in the stratosphere and can be used for telecommunications, broadcasting and environmental measurements. Using HAPs in mobile communications is a promising scheme because it takes the advantages of using satellites but at lower altitudes [1–5]. On the other hand, the conventional terrestrial system suffers from coverage problems which are mostly eliminated using HAPs. The HAPs cellular design reaches its end by determining the pointing angles corresponding to the coverage antennas and their beamwidths. Concerning this point, one must take into consideration the proper radio coverage which means how the cells overlap and the shape the cellular structure at the edges of the coverage area. In the terrestrial cellular structure, the geometry of the formed cells is defined by considering its hexagonal shape and geometrically it is easy to find the other cells locations, however in the case of HAPs system, each cell has an elliptical shape defined by the half-power contour of its corresponding beam [6]. This elliptical cell will increase in area when directing its beam for lower-elevation angle coverage and the degree of cell inflating depends on the beam direction and the type of antenna used. Therefore we face a problem of non-fixed cell area when utilizing the same type antennas (i.e., all antennas have equal beamwidths) and we cant utilize the terrestrial cellular design directly to determine the cells locations. Previous studies [5,6] design HAPs cellular system by using the terrestrial cellular design and adjusting the distances between cells in a try and error fashion until a mostly uniform cellular structure is obtained (with almost non extra cells overlap) and without using defined algorithm or equations governing this cell-location modification. Therefore, this paper is devoted to give an algorithm that defines the proper cells locations in the design of HAPs cellular system when using the same type of coverage antennas to construct these cells which may be spot-beam antennas or antenna arrays. This algorithm uses the subplatform cell radius which calculated in the system design as a starting point for other cells generation. It also takes into consideration the increase in cell dimensions at lower elevation angles. The paper is arranged as follows; Section 2 discusses the use of both spot-beam antennas and phased antenna arrays [7,8] in the HAP radio coverage for cells formation and the geometry of the cell footprint. Section 3 reviews the terrestrial hexagonal cellular structure and its mathematical relations. Section 4 discusses the proposed algorithm and the generated pointing angles for a case study showing the generated cellular structure and finally in Section 5 we introduce some concluding remarks.

2. HAPS RADIO COVERAGE

The HAPs system adopts the directional as well as antenna arrays to construct its ground cells. Directional antennas may be in the form of parabolic reflectors, horn antennas, or any other suitable antenna that gives the desired directional pattern. The major parameters in the system design concerning directional antennas are gain, bandwidth, beamwidth, and sidelobe level. In this paper we assume that we have the proper directional antenna that gives the desired parameters and we concentrate on how the cells can be arranged on the ground to have most uniform cellular pattern. The uniformity of the cellular structure when using the same type of antenna in all cells is important especially when we plan a network containing a number of HAPs each having its own cellular structure. The use of directional antennas has some advantages such as its practical availability and simplicity but on the other hand a failure in any of them results in a coverage hole due to the absence of the beam used in forming its cell. The other type of antenna structure that can be used in the HAP radio coverage is the planar antenna arrays. Ground cells can be formed by directing a beam formed by a phased array which has a widespread use. Any of the formed beams is constructed by a number of antenna elements therefore any element failure in the array will slightly distort the beam pattern (the beam will have slightly larger beamwidths) and this can be an advantage compared with the use of directional antennas. We face a problem when using phased arrays that is the increase in beamwidths for lower elevation angle coverage. This increase in beamwidths will flatten the cells. Another technological disadvantage of antenna arrays is the complexity of the beamforming network used in constructing the beams. Figure 1 displays the footprint of a beam formed by any of the mentioned antennas onboard the HAP. The platform height is h km high and a beam oriented generally towards (θ_o, ϕ_o) forms that cell. In general the cell can be considered as an ellipsoid with major and minor axes b and a respectively. To determine the dimensions of that ellipse we first determine both values of its axes (i.e., b and a). The value of b can be deduced from Fig. 1 as follows

$$\begin{aligned} b \;=\; & R\left(\sin^{-1}\left(\left(1+\frac{h}{R}\right)\sin\left(\theta_o+\frac{BW_\theta}{2}\right)\right)\right. \\ & \left. -\sin^{-1}\left(\left(1+\frac{h}{R}\right)\sin\left(\theta_o-\frac{BW_\theta}{2}\right)\right)-BW_\theta\right) \end{aligned} \tag{1}$$

where R is the earth radius and the 3 dB beamwidth in the elevation plane is denoted by BW_θ and that of the azimuth plane is BW_ϕ. An expression of a can be deduced as :

$$a = 2h\sec(\theta_c)\tan(BW_\phi/2) \tag{2}$$

where

$$\theta_c = \tan^{-1}\left(\tan\left(\theta_o-\frac{BW_\theta}{2}\right)+\frac{b}{2h}\right) \tag{3}$$

From Eq. (1) and Eq. (2), we can determine both b and a from the antenna beamwidths, direction and the platform altitude. The

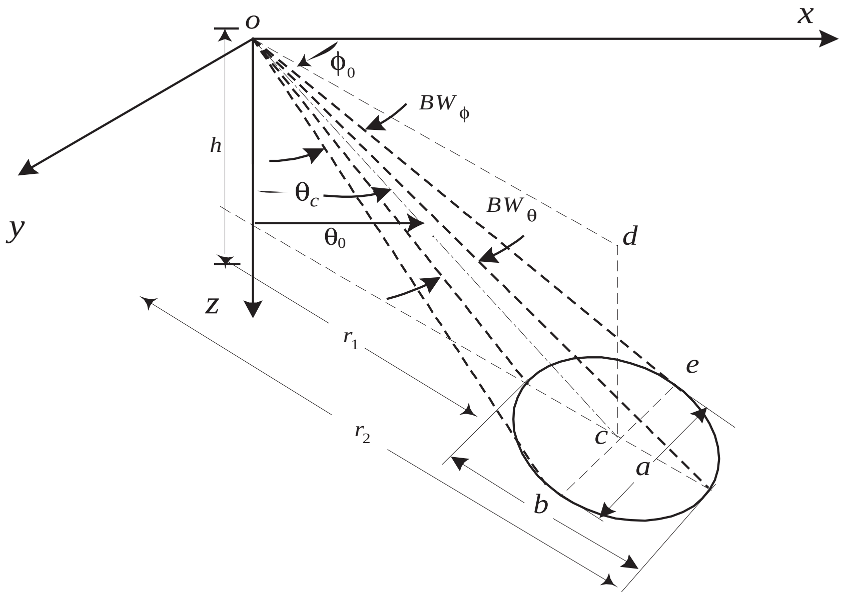

Figure 1. HAP cell footprint.

equation governing the boundary of that ellipse is given by:

$$\left(\frac{x\cos(\phi_o)-y\sin(\phi_o)-h\tan(\theta_c)}{b/2}\right)^2+\left(\frac{y\cos(\phi_o)+x\sin(\phi_o)}{a/2}\right)^2=1 \tag{4}$$

and the cell area is given by:

$$\begin{aligned} A_r &= \pi h^2\tan\left(\frac{BW_\theta}{2}\right)\tan\left(\frac{BW_\phi}{2}\right)\sec^2(\theta_o) \\ &\quad \times\sec(\theta_c)\Big/\left(1-\tan^2(\theta_o)\tan^2\left(\frac{BW_\theta}{2}\right)\right) \end{aligned} \tag{5}$$

In the cellular design we must have information about the expected user density, number of carriers and channels. Whether TDMA (GSM) or CDMA (UMTS) or other multiplexing technique used we reach the end of such design by defining the cell radius or area which defines the antenna requirements. Next to that step is the cellular system construction or layout with the suitable reuse pattern.

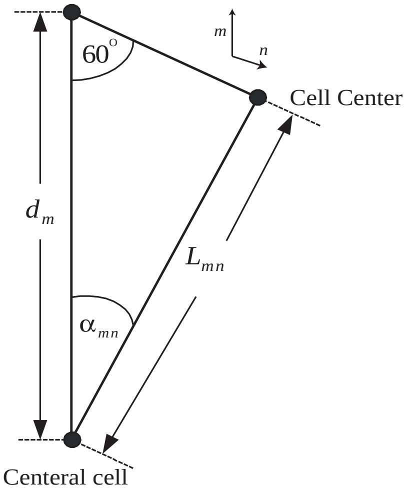

Figure 2. Coordinate system for cell location determination.

3. CELLULAR STRUCTURE FOR TERRESTRIAL MOBILE RADIO

The most appropriate shape that approximates the boundary of the terrestrial cell is the hexagonal one. Figure 2 displays a coordinate system used to define the hexagonal cellular layout geometry where m and n are integers used to define the cell location or coordinates. In general each cell has a separating distance from the center of the subplatform cell (i.e., the cell underneath the platform) given by L_{mn} and an azimuth angle, α_{mn}, measured from the vertical axis, m, to the line connecting the center of that cell with the center of the subplatform cell. From the geometry of this coordinate system we can define L_{mn} as:

$$L_{mn} = d_1\sqrt{m^2 + n^2 - mn} \tag{6}$$

where $d_1 = r_o\sqrt{3}$ and r_o is the central cell radius.

Also α_m can be given by:

$$\alpha_{mn} = \cos^{-1}\left(\frac{2m - n}{2\sqrt{m^2 - mn + n^2}}\right) \tag{7}$$

The indices m and n are used only in the first sector of the tier and for the remainder cells in the same tier we can easily calculate their locations by simply rotating the structure by multiple of 60° in the azimuth plane with the same central distance. Figures 3 and 4 displays

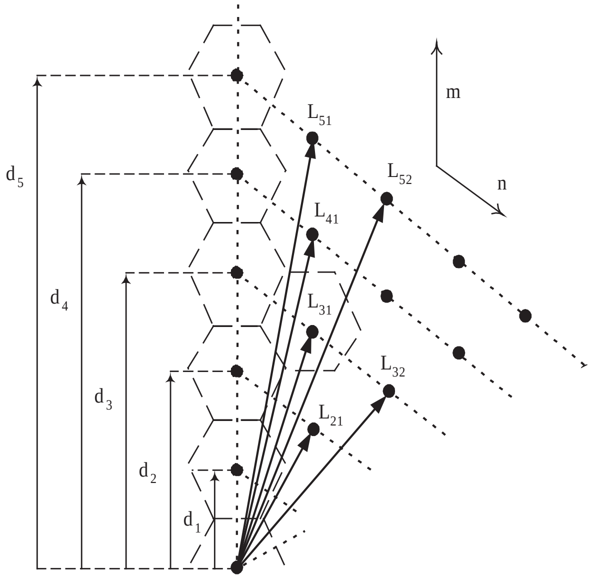

Figure 3. Central distance L_{mn} and radial distance d_m for some cells located in the first sector.

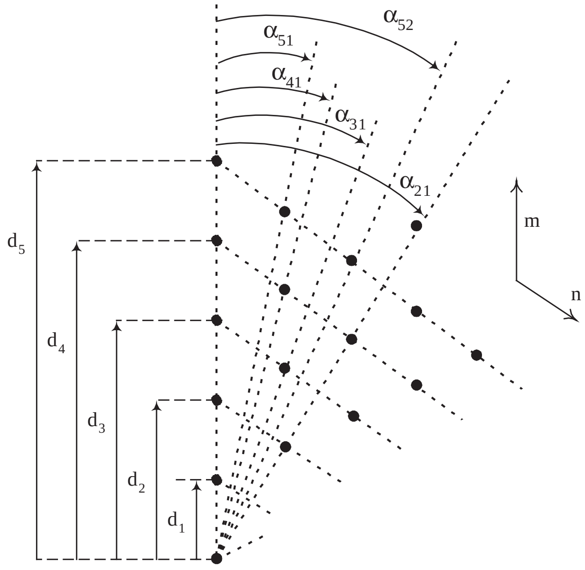

Figure 4. Central azimuth angle α_{mn} for some cells located in the first sector.

some values of cell central distance and azimuth angles respectively in the first sector. For the tier of order m, we find that n will take the values $0, 1, 2, \ldots m$. Table 1 displays the values of the central azimuth angle of cells located in the first sector of the six sectors tiers with different orders.

Table 1. Cell azimuth angle for cells in the first sector.

Tier order	**Cell azimuth angle α_{mn} in Degrees**					
	Cell number ***n***					
m	**0**	**1**	**2**	**3**	**4**	**5**
1	0°	-	-	-	-	-
2	0°	30°	-	-	-	-
3	0°	19.11°	40.89°	-	-	-
4	0°	13.89°	30°	46.1°	-	-
5	0°	10.89°	23.41°	36.58°	49.16°	-
6	0°	8.948°	19.106°	30°	40.89°	51.05°

4. BEAM-DIRECTION DETERMINATION ALGORITHM

Designing HAP cellular system includes teletraffic study and the needed cellular structure is constructed by defining each cell location and the corresponding antenna parameters used in the radio coverage such as beamwidth, gain, bandwidth and the pointing angles or the beams directions. We introduce here an algorithm that generates the antenna pointing angles taking into consideration the uniformity of the radio coverage such as minimal coverage gaps and overlap. The algorithm starts with the value of the inner cell radius r_o, then we calculate the first tier cells using the conventional terrestrial relations discussed in the last section and make some corrections due to the cell flattening. For the other outer tiers we update the central distances by the new expected major axis of the cell. The algorithm calculates the cells on the vertical axes (i.e., the cells having $\alpha_m = 0$ degree). The other cells locations in the outer tiers that having azimuth angles other than zero are determined by taking the ratio of the corresponding cells radial distance d_m with L_{m0} calculated from Eq. (6). which is then multiplied by the distance L_{mn} to find the cell location with its azimuth α_{mn} given in Eq. (7). This algorithm can be summarized with its relations in the following points:

1- From the teletraffic information find the central cell radius r_o and the needed antenna beamwidths BW_θ and BW_ϕ.

2- Calculate radial distance $d_1 = r_o\sqrt{3}$,

3- Find $\theta_o = \tan^{-1}\left(\frac{d_1}{h}\right)$ and b_1 using Eq. (1),

4- Calculate θ_c and a_1 for the first tier,

5- Update the radial distance d_1 with $d_1 = \frac{\sqrt{3}}{2}\left(r_o + \frac{b_1}{2}\right)$

6- Update θ_o with $\theta_o = \tan^{-1}\left(\frac{d_1}{h}\right)$

7- Determine the final values of a_1 and b_1

For the other outer tiers the algorithm proceeds as follows:

1- Start with $d_m = d_{m-1} + \frac{\sqrt{3}}{2}b_{m-1}$, where m is the order of the tier.

2- Find θ_o, b_m, θ_c, and a_m,

3- Update d_m with $d_m = d_{m-1} + \frac{\sqrt{3}}{4}(b_m + b_{m-1})$

4- Calculate the final values of θ_o, b_m, θ_c and a_m.

5- For other non 60°-axes cells we find the ratio d_m/L_{m0}, where L_{m0} is calculated from Eq. (6), with $n = 0$ and m is the order of the tier, then multiply this ratio by L_{mn} which gives the needed cell radial distance $L'_{mn} = \frac{d_m}{L_{m0}}L_{mn}$,

6- From the value of L'_{mn} calculate $\theta_o = \tan^{-1}\left(\frac{L'_{mn}}{h}\right)$, b_m, θ_c, and a_{mn}

The algorithm assumes that all the antennas used are of the same beamwidth which is useful for economical considerations. Figures 5 and 6 display layouts of cellular structure consisting of seven tiers formed by 169 cell for two cases of antennas. In Fig. 5 we utilize a square antenna array of 20 × 20 elements and in Fig. 6 we utilize spot-beam antennas each of beamwidth equals 5.0781 degrees which is the same beamwidth generated from 20 × 20 array for the central cell. As depicted in these figures the use of antenna arrays in the radio coverage will face a problem of more cell flattening compared with spot beam antenna of fixed beamwidth but on the other hand a larger area is covered with the same number of cells. This difference appears clearly when we use a fixed number of elements in the array to form all cells. The two figures shows also the uniformity of the radio coverage in both cells overlap and the outermost tier edges. The uniformity of the outermost tier helps well in arranging and neighboring other HAP cellular structures as shown in Fig. 7 where there is a weak possibility of coverage holes.

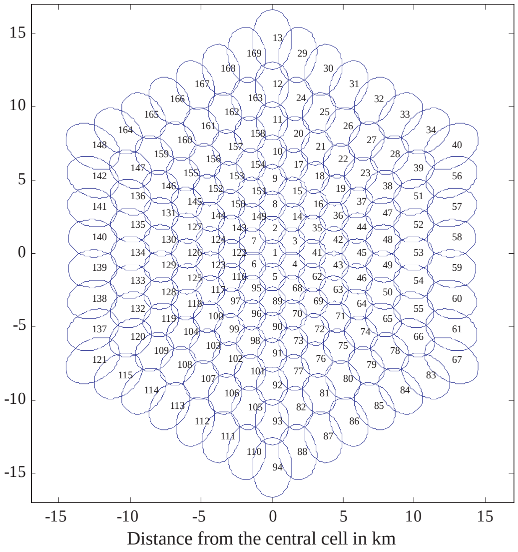

Figure 5. HAP cellular layout constructed by 169 cell using 20 × 20 antenna array.

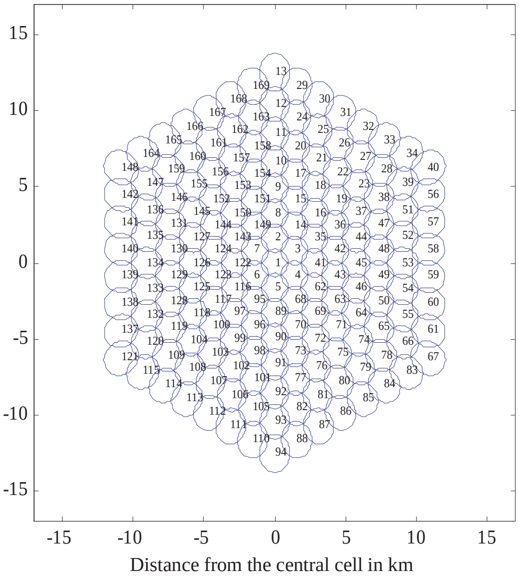

Figure 6. HAP cellular layout constructed by 169 cell using spot-beam antennas of 5.0781° beamwidth.

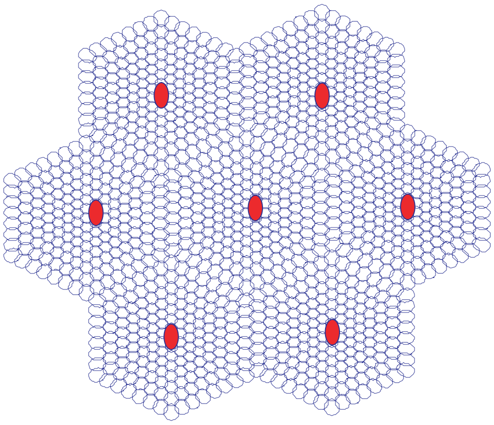

Figure 7. Layout of seven HAPs linked together to cover larger area and showing their uniformity at edges.

5. CONCLUSION

High altitude platforms is an emerging technology for different types of communications especially mobile cellular radio. When used as a multiple base station unit it needs some optimization in directing the coverage beams to satisfy mostly uniform radio coverage and an algorithm for this purpose is introduced in this paper. The proposed algorithm updates the cells locations with their corresponding dimensions especially the cell major. The algorithm has shown from the design figures the uniformity in radio coverage with minimal coverage holes, cell overlapping and at the edges of the outermost tier that helps linking more HAPs without coverage problems.

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