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GEOMETRICAL CORRECTION FOR CELL DEPLOYMENT IN STRATOSPHERIC CELLULAR SYSTEMS

S. Aljahdali, M. Nofal, and Y. Albagory*

College of Computers and Information Technology, Taif University, Saudi Arabia

Abstract—In this paper, cellular communications from Stratospheric platforms (SPs) is studied, and the coverage footprint analysis and design is demonstrated. In the analysis, two coverage schemes are introduced; flat-earth and real-earth models and cell footprint are determined in each case. The flat-earth provides simple footprint equations describing the cell dimensions especially for the cells of higher elevation angles while more accurate coverage equations, which well determine the geometry of the cells of lower elevation angles, can be obtained from the real-earth scheme. The design of a cellular system using the proposed coverage models is then introduced through a procedure that determines the cells locations and dimensions on the ground according to the teletraffic information. The procedure takes into considerations the cell broadening when going outwardly from the central cell to the outer lower elevation cells and constructs a cellular layout that has the most proper cells overlap and uniform coverage edges, which helps the linking between different SPs coverage areas.

1. INTRODUCTION

In recent years, Stratospheric platforms (SPs) has gained considerable attention in broadband mobile communications. These platforms are located 17–20 km above the earth's surface and can provide variety of applications. The demand for SPs has increased as they have most advantages of the conventional systems such as terrestrial mobile radio and satellite systems while eliminating most of their problems as shown by many studies [1–7]. It is expected that SPs will play an important role in the future wireless communications beyond 3G systems [7]. One of the important issues in SPs communications is to provide

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* Corresponding author: Yasser Albagory (y.albagory@tu.edu.sa).

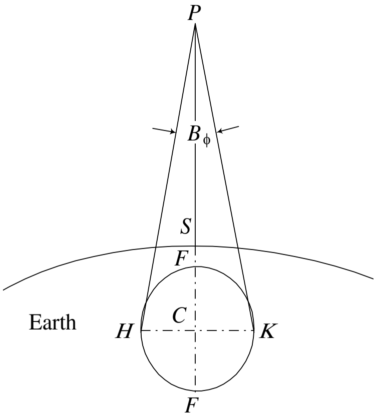


Figure 1. SP cell footprint.

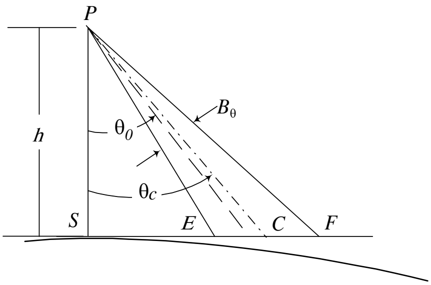


Figure 2. Flat ground approximation geometry.

higher system capacity, which can be obtained through utilizing the frequency reuse over the covered area. According to the reuse factor and the needed carrier-to-interference ratio (CIR), the cellular system will be constructed defining each cell location and dimensions. In the terrestrial mobile system, the cells are defined by a hexagonal shape while in the case of SPs, the cell footprint has an ellipsoidal shape [2] which has a major and a minor axes defining its dimensions. The SPs ground cells can be formed using either spot-beam antennas or phased arrays, and the cell boundary is well defined by the beam pattern of the used antenna. This cell boundary may be taken as the half power contour on the ground, and the users corresponding to that cell are located within that contour. A difficulty in deploying this cellular system is that the cell footprint increases as the elevation angle decreases, which requires some modification in pointing the beams of these cells. Another point worth noting is that most of the radio coverage studies done for SPs had approximated the earth as a flat surface as the platform altitude is much smaller than the earth's radius, while for large coverage areas we need an accurate cell dimensioning taking into considerations the earth curvature. Therefore, this paper is arranged as follows: in Section 2 the flat-earth approximation is depicted, while Section 3 discusses the real-earth coverage. Section 4 analyzes the two coverage models. In Section 5, we discuss the design of SPs cellular system, while in Section 6, we analyze the terrestrial cellular design. In Section 7, the SPs cellular-layout procedure is proposed, and finally Section 8 gives some concluding remarks.

2. FLAT-EARTH COVERAGE MODEL

The SPs wireless communication system may utilize directional antennas as well as phased antenna arrays to construct cellular footprint. Directional antennas may be in the form of parabolic reflectors, horn antennas, or any other suitable antennas that give the desired directional pattern. The use of directional antennas has some advantages such as practical availability and simplicity, but on the other hand, a failure is observed in one of their results in a coverage hole due to the absence of beam used to form its corresponding cell. The ground cells footprints can also be formed by directing a beam using phased arrays which have a widespread use. Each formed cell is constructed by a number of antenna elements, and any element failure in the array will slightly distort the beam pattern (the beam will have slightly larger beamwidths), but the element failure can also be an advantage compared to directional antennas because it will not result in a coverage gap due to element failure. In most literature [2, 8] dealing with SP footprint, the SPs station is located at an altitude about 20 km high, which is very small compared with the earth's radius; therefore the earth is approximated as a flat surface as shown in Fig. 1. In this figure, the footprint of a beam formed by any of the mentioned antennas onboard the SP is shown. The cell depicted in Fig. 2 is defined by the coverage beam that has a direction of θ_o and cross section beamwidth of B_θ and B_ϕ, and the projection of the beam on the ground will be an ellipse that has a major axis EF and minor axis HK. Denoting the distance EF as b_F which can be deduced as

$$b_F = h\left(\tan\left(\theta_o + \frac{B_\theta}{2}\right) - \tan\left(\theta_o - \frac{B_\theta}{2}\right)\right) \tag{1}$$

where the subscript F stands for flat ground approximation, and h is the platform altitude in km. The cell center, C, is located by an angle from the platform given by

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

and if the cell's minor axis distance HK is denoted by a_F, it can be given by

$$a_F = 2h\sec(\theta_c)\tan\left(\frac{B_\phi}{2}\right) \tag{3}$$

These two quantities (i.e., the minor and major axes) will define the cell shape, and this assumption can be used for smaller and moderate SP coverage areas, but when the coverage area increases, the approximation error will increase and can no longer be used.

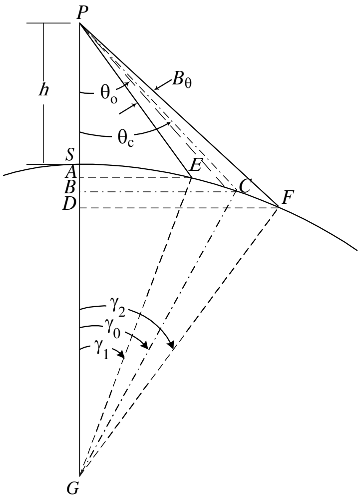


Figure 3. Curved earth coverage geometry.

3. REAL-EARTH COVERAGE MODEL

In the following section, the earth curvature is taken into consideration which predicts the cell footprint well. A side view is shown in Fig. 3, which depicts the geometry used to define the cell parameters. In this figure, the major axis will be the arc on the earth's surface between the two ground central angles γ_1 and γ_2. These angles can be deduced as

$$\gamma_1 = \sin^{-1}\left(\left(1+\frac{h}{R}\right)\sin\left(\theta_o - \frac{B_\theta}{2}\right)\right) - \theta_o + \frac{B_\theta}{2} \tag{4}$$

and

$$\gamma_2 = \sin^{-1}\left(\left(1+\frac{h}{R}\right)\sin\left(\theta_o + \frac{B_\theta}{2}\right)\right) - \theta_o - \frac{B_\theta}{2} \tag{5}$$

where the cell center has a ground central angle given by

$$\gamma_o = \frac{1}{2}\left(\gamma_1 + \gamma_2\right) \tag{6}$$

and we can define the distance PB as

$$PB = h + R\left(1 - \frac{1}{2}\left(\cos(\gamma_1) + R\cos(\gamma_2)\right)\right), \tag{7}$$

and the distance BC will be

$$BC = \frac{1}{2}R\left(\cos(\gamma_1) + R\cos(\gamma_2)\right)\tan\left(\gamma_o\right) \tag{8}$$

Therefore, the slant distance connecting the platform to the cell center will be

$$PC = \sqrt{PB^2 + BC^2} \tag{9}$$

and the cell major axis, b_C, can be defined as

$$b_C = EF = R\left(\gamma_2 - \gamma_1\right) \tag{10}$$

or

$$\begin{aligned} b_C \ = \ & R\left(\sin^{-1}\left(\left(1+\frac{h}{R}\right)\sin\left(\theta_o + \frac{B_\theta}{2}\right)\right)\right. \\ & \left. -\sin^{-1}\left(\left(1+\frac{h}{R}\right)\sin\left(\theta_o - \frac{B_\theta}{2}\right)\right) - B_\theta\right) \end{aligned} \tag{11}$$

where the subscript c stands for curved-earth, and in this case the value of θ_c will be

$$\theta_c = \tan^{-1}\left(\frac{BC}{PB}\right) \tag{12}$$

or

$$\theta_c = \tan^{-1}\left\{\frac{\tan(\gamma_o)}{2\left(1+\frac{h}{R}\right)/(\cos(\gamma_1)+\cos(\gamma_2)) - 1}\right\} \tag{13}$$

therefore, the cell minor axis, a_C, will be

$$a_C = HK = 2PC\tan\left(\frac{B_\phi}{2}\right) \tag{14}$$

or

$$a_C = 2h\sec\left(\theta_c\right)\tan\left(\frac{B_\phi}{2}\right) \tag{15}$$

which can also be given by

$$\begin{aligned} a_C \ = \ & 2R\tan\left(\frac{B_\phi}{2}\right)\left(\left(1+\frac{h}{R}-\frac{1}{2}\left(\cos\left(\gamma_1\right)+\cos\left(\gamma_2\right)\right)\right)^2\right. \\ & \left. +\frac{1}{4}\left(\cos\left(\gamma_1\right)+\cos\left(\gamma_2\right)\right)^2\tan^2\left(\gamma_o\right)\right)^{1/2} \end{aligned} \tag{16}$$

4. COMPARISON

Figures 4(a) and 4(b) depict the variations of the cell major axis with the beam direction, θ_o, at different beamwidths, B_θ, for both coverage schemes using directional spot-beam antennas. The variations in this figure indicate the increase in the footprint with increasing both the beam direction and the beamwidth. The difference (or the absolute distance error) between the two quantities in km is shown in Fig. 5(a) while the relative error in the cell major axis between the two models may be defined as:

$$\varepsilon_b = \frac{b_C - b_F}{b_C} \times 100\% \tag{17}$$

where its variation with both the beam direction and beamwidth is shown in Fig. 5(b). In this figure, the error may approach 2% of the major axis for beamwidth of 20° at a beam direction of about 60° which corresponds to 700 meter difference. The system design will be sensitive to the large difference between the two expected major axis values in the two schemes and this appears especially in the cells at the edges of the SP coverage. On the other hand, the error is much smaller for both the inner cells and cells of narrower beamwidth. For example, a beamwidth of 5° generates cells that have an error not exceeding 12 meters for direction less than 40° as depicted in Fig. 5(a).

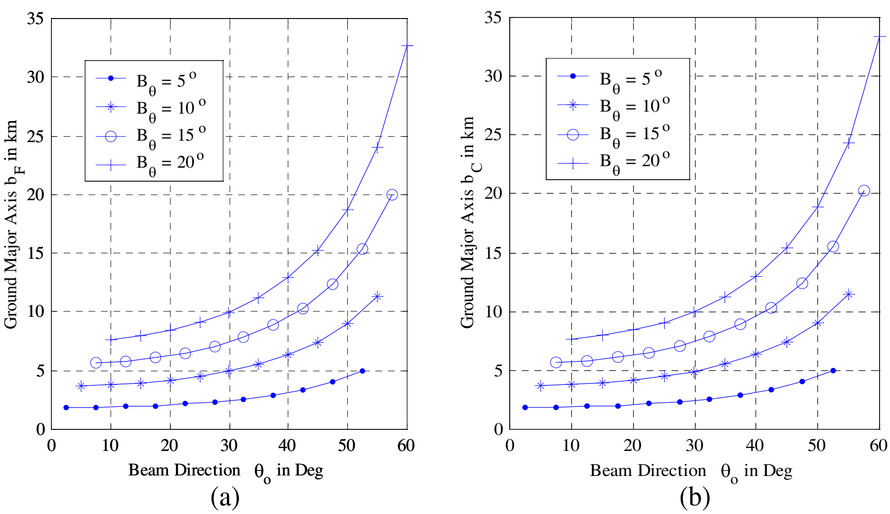


Figure 4. (a) b_F variation with beam direction at different beamwidths. (b) b_C variation with beam direction at different beamwidths.

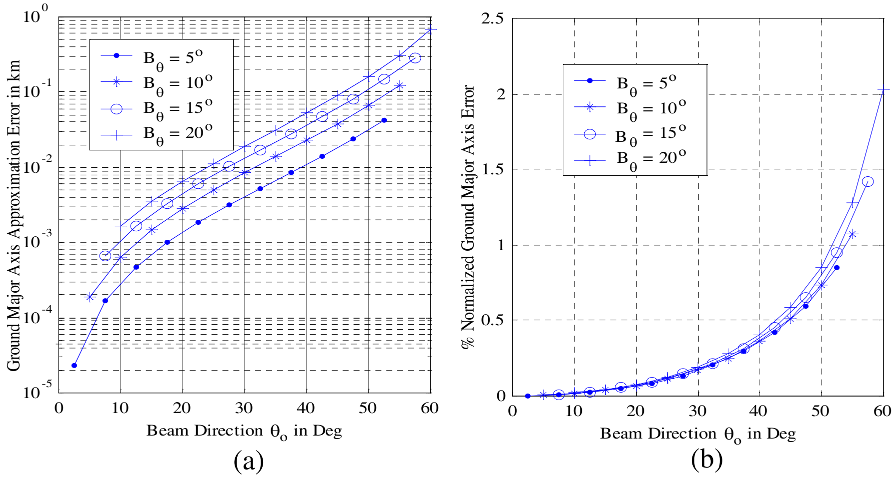


Figure 5. (a) Ground approximation error variation with beam direction at different beamwidths. (b) Relative error variation with beam direction at different beamwidths.

Similarly, the error in the minor axis is also given by

$$\varepsilon_a = \frac{a_C - a_F}{a_C} \times 100\% \tag{18}$$

The same analysis is done for the cell minor axis as depicted in Figs. 6(a) and 6(b), and the errors (absolute and relative) for the two models are shown respectively in Figs. 7(a) and 7(b).

One can therefore utilize the simple equations used in the flat ground approximation for the range of acceptable error (such as for cells near the subplatform point) while for the outer cells, we can utilize the curved earth equations that is optimizing the use of both models in subsequent cellular design.

5. SPS RADIO COVERAGE DESIGN

The major parameters in the system design concerning directional antennas are gain, bandwidth, beamwidth, and sidelobe level. In the following sections, we assume that we have directional antennas or antenna arrays that give the desired parameters, and we discuss how the cells can be arranged on the ground to have most uniform cellular coverage. When using the same type of antenna in all formed cells, the uniformity of the cellular structure is important especially when we plan a network containing a number of SPs. We face a problem

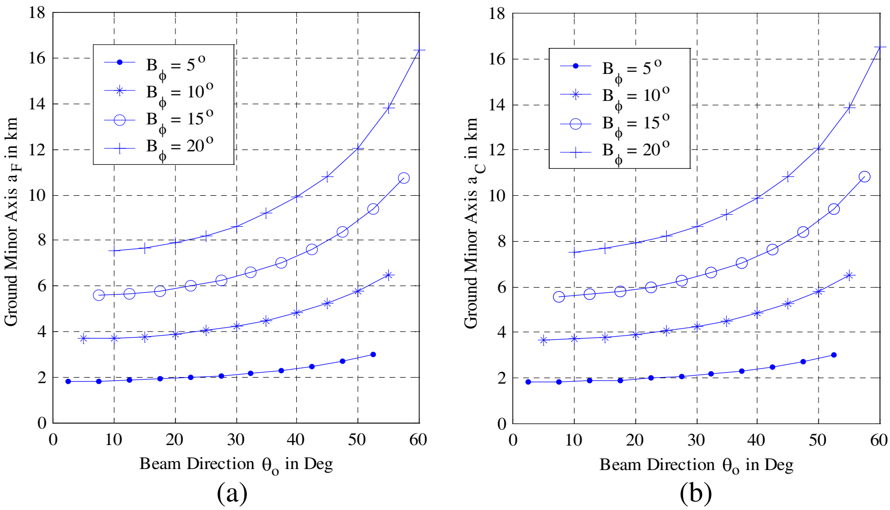


Figure 6. (a) a_F variation with beam direction at different beamwidths. (b) a_C variation with beam direction at different beamwidths.

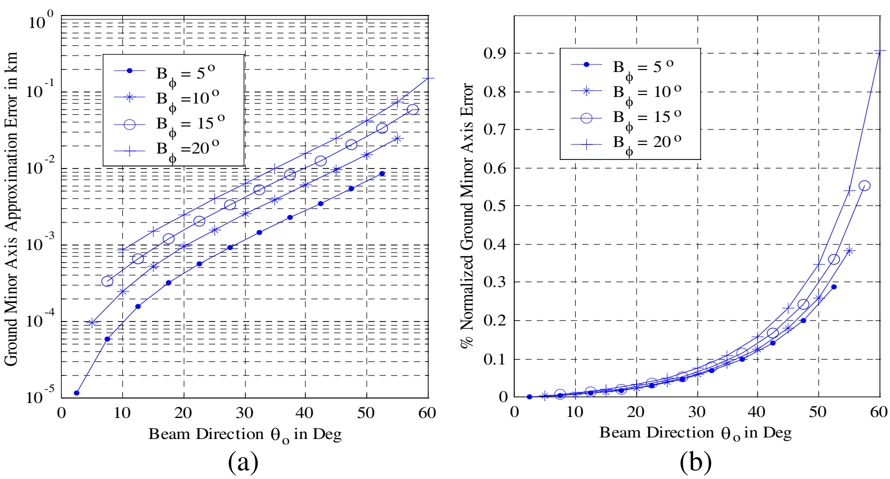


Figure 7. (a) Absolute error variation with beam direction at different beamwidths. (b) Relative error variation with beam direction at different beamwidths.

when using phased arrays that is the increase in beamwidths for cells of lower elevation angles (i.e., the outer cells) which flatten that cells.

In the cellular design, we must have the teletraffic information about the coverage area under consideration and available radio resource, and the complete cellular design defines the parameters of the coverage cells which in turn defines the antenna requirements. In the terrestrial cellular systems, the cell is approximated as a hexagonal shape of a certain corner radius which simplifies the analysis, but in the case of SP system, the cell will be of circular or elliptical shape. How can we construct the cellular layout? If we utilize the terrestrial geometry, the cells will overlap more and more when going towards the outer cells due to the increase in the cell area. Therefore, there must be adjustments for the calculated terrestrial system geometry to have a proper SP cellular structure, and these adjustments will be a function of the cells locations. To do this, we start defining the hexagonal cellular geometry and parameters of the cells in that system and then modifying these parameters to suit the SP system.

6. TERRESTRIAL CELLULAR STRUCTURE

The hexagonal cellular layout geometry is divided into six homogenous sectors, and for each sector, we use integers m and n to define the cell location or coordinates as shown in Fig. 8. In general, each cell has a separating distance from the center of the central cell 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 central

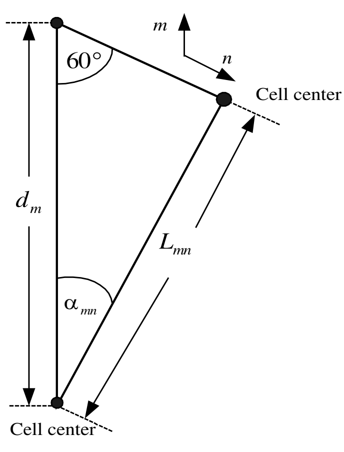


Figure 8. Coordinate system for cell location determination.

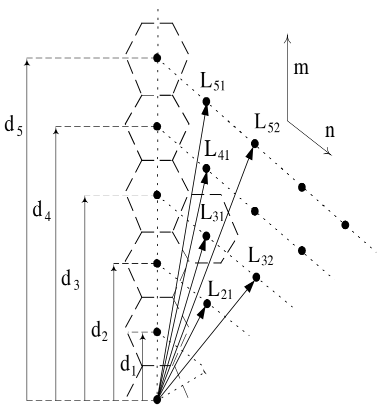


Figure 9. Central distance L_{mn} and radial distance d_m for some cells located in the first sector cell.

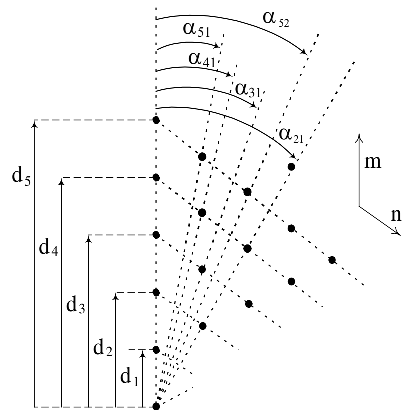


Figure 10. Central azimuth angle α_{mn} for some cells located in the first sector.

cell. From the geometry of this coordinate system, we can define L_{mn} as:

$$L_{mn} = d_1 \sqrt{m^2 + n^2 - mn} \tag{19}$$

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

Also α_m can be given by:

$$\alpha_{mn} = \cos^{-1}\left(\frac{2m - n}{2\sqrt{m^2 - mn + n^2}}\right) \tag{20}$$

Figures 9 and 10 demonstrate some of the cell central distances 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, ... 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.

7. SPS CELLULAR SYSTEM DESIGN

Designing SPs cellular system means 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. An algorithm is proposed, which generates the antenna pointing angles taking into consideration the uniformity of the radio coverage such as minimizing the coverage gaps and overlap. The algorithm proceeds outwardly from the central cell and starts with the value of the central cell radius r_o, then we calculate the first tier

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

Tier order m	Cell azimuth angle α_{mn} in Degrees					
	Cell number n					
	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 °	19.11°	30 °	40.89°	51.05°

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, 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. (19), which is then multiplied by distance L_{mn} to find the cell location with its azimuth α_{mn} given in Eq. (20). 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 B_θ and B_ϕ.

2- Find the initial radial distance $d_1 = r_o\sqrt{3}$.

3- Find $\theta_o = \tan^{-1}(\frac{d_1}{h})$ and b_{c1} using Eq. (11).

4- Update the radial distance d_1 with $d_1 = \frac{\sqrt{3}}{2}(r_o + \frac{b_{c1}}{2})$.

5- Updateθ_o with $\theta_o = \tan^{-1}(\frac{d_1}{h})$.

6- Determine the final values of a_{c1} and b_{c1}.

For the other outer tiers, the algorithm proceeds outwardly, and if the cells are located on the sectors edges (i.e., their azimuth angles are 0°, 60°, 120°, etc.), then the cells locations are calculated as follows:

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

2- Find θ_o and b_{cm}.

3- Update d_1 with $d_m = d_{m-1} + \frac{\sqrt{3}}{4}(b_{cm} + b_{\text{cm}-1})$.

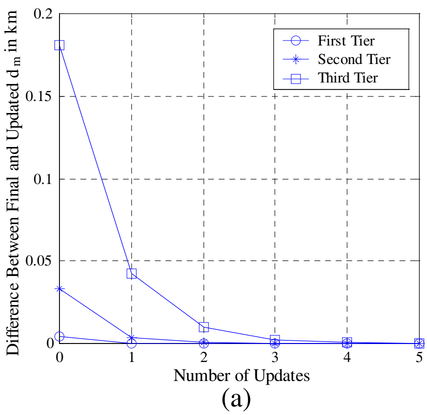
4- Calculate the final values of θ_o, $b_{\rm cm}$,θ_c, and $a_{\rm cm}$.

5- For other non 60°-axes cells we find the ratio d_m/L_{m0}, where L_{m0} is calculated from Eq. (19), 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:

$$L'_{mn} = \frac{d_m}{L_{m0}} L_{mn} \tag{21}$$

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

The updating steps in the algorithm may be repeated several times to reach the final cell locations. Figs. 11(a) and 11(b) depict the convergence in calculations of the cell distance d_m for the first, second and third tiers for an array's 10×10 elements and spot-beam antennas of 10° beamwidth. In both figures, the final value of d_m may be reached in one updating especially for the internal tiers while it may need several updates for the outer ones. Figs. 12 and 13 display layouts of cellular structure consisting of seven tiers formed by 169 cells for two cases of antennas. In Fig. 12, we utilize a square antenna array of 20×20 elements, and in Fig. 13, we utilize spot-beam antennas of 5.0781° beamwidth 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 than spot beam antenna of fixed beamwidth. On the other hand, a larger area is covered with the same number of cells.



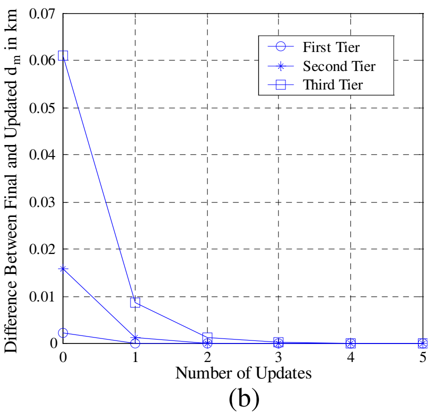


Figure 11. (a) Convergence of the cells distance d_m for the first three tiers constructed by an antenna array 10×10 elements. (b) Convergence of the cells distance d_m for the first three tiers constructed by spot-beam antennas of 10.16° beamwidth.

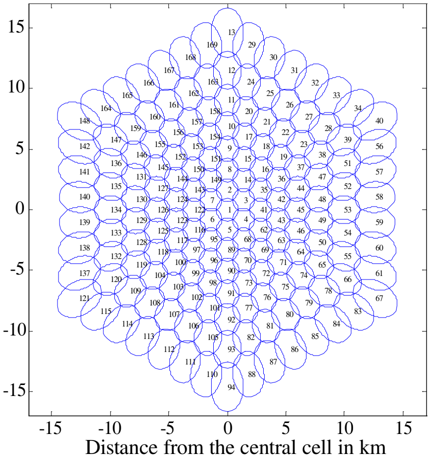


Figure 12. SP cellular layout constructed by 169 cell using 20×20 antenna array.

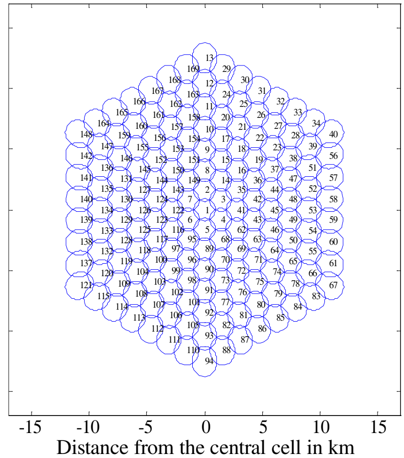


Figure 13. SP cellular layout constructed by 169 cell using spot-beam antennas of 5.0781° beamwidth.

This difference appears clear when we use a fixed number of elements in the array to form all cells. Also, the two figures show uniformity in the overlap regions between cells in both cases and the coverage at the outermost tier edges. The uniformity of the outermost tier helps well in arranging and neighboring other SP cellular structures where there is a lower possibility of coverage holes between different SPs footprints.

8. CONCLUSION

Cellular communications from high altitude platforms (SPs) have been discussed, and the geometry of the coverage footprint is analyzed and demonstrated. Two coverage configurations are discussed depending on the approximation of the earth's surface, flat-earth and curved-earth coverage. In flat-earth model, there are simple footprint equations describing the cell dimensions especially for cells of higher elevation angles while more accurate coverage equations can be obtained from the curved-earth scheme which takes into consideration the curvature of the earth and well determine the geometry of the cells of low elevation angles. The two models can be used for cell dimensioning where one can utilize flat earth model for cells of higher elevation angles while for wider coverage beams and lower elevation angles, the other curved-earth model can be utilized. Dimensioning the cells will be very important in the next step of the cellular design introduced through an algorithm that determines the cells locations and dimensions on the ground according to the teletraffic information. The algorithm takes into considerations the cell broadening when increasing its going outwardly from the central cell to the outer tiers of low-elevation angle cells. A cellular layout is then deployed and has most proper cells overlap and uniform coverage at the edges which helps linking between different SPs radio coverages.

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