Compensative Mechanism Based on Steerable Antennas for High Altitude Platform Movement

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***Abstract* – Because of the complexity of stratosphere, HAPs might inevitably encounter relative motion with respect to the ground, which leads to variation of quality of service in the intended coverage area. Models for predicting the geographical coverage in the cases of shift horizontally and vertically, yaw, roll and pitch of HAP are presented in this work. And also the mechanisms of compensation based on steerable antennas in these cases are explored. The mechanism is then applied to a 127 cell architecture, with a cell cluster size of four. It can be seen from the simulation result that by employing the steerable antenna correction mechanism, the movement can be compensated to some degree in order to guarantee effective coverage of the service area.**

***Index Terms* – High Altitude Platform (HAP), movement, Steerable antenna, Carrier to Interference ratio (CIR)**

I. INTRODUCTION

With an increasing demand for broadband multimedia application, service providers are looking to utilize High Altitude Platforms (HAPs) for the provision of broadband wireless access, which have the advantages of both satellite and terrestrial communication systems. HAPs can be either airships or aircrafts soaring in the stratosphere at an altitude between 17 and 22 km above the Earth's surface. They are quick to deploy and can provide line-of-sight channels over a geographic service area of approximately 60 km diameter. [1]

High altitude platform communication system can employ a cellular architecture, which is similar to that of terrestrial system. This mechanism can provide overall system capacity by using a large number of wireless transceivers, each using a directional antenna to create cells on the ground [2]. The radiation characteristics of the antennas should be aperture types, with low sidelobes and a sharp roll-off in the main lobe, for sake of minimizing interference between cells. However, too high a directivity will lead to excessive power roll-off at cell edge. Therefore, to chose appropriate directional antennas for HAPs is of great importance in satisfying CIR requirement in a service area.

Moreover, because of the complexity of stratosphere, the HAP might inevitably encounter sudden turbulence. Therefore, although necessary payload is employed against possible movement, HAP system is still of relatively loose station keeping characteristics. HAPs may suffer from shift horizontally, vertically, or even rotation, which leads to undesirable decline in the quality of service. Payload for dynamically modulating the steerable antennas to point to the intended area is necessary to guarantee quality of service.

II. HAP MOVEMENT MODELS

A. *Scenario model for HAP system*

In this scenario, a HAP is soaring at a height of 20km. The radius of the coverage is 30km which is divided into 127 cells, each with an antenna on the HAP providing effective coverage (See Fig. 1).

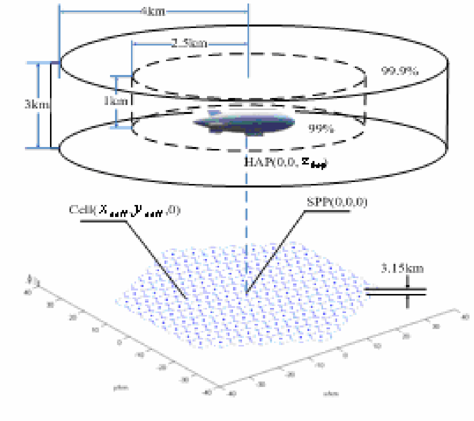

Fig. 1 Probable position for a HAP

The position of a HAP must be confined to a certain area to guarantee effective service by using station-keeping mechanism and attitude control payload. NeliNet[3] Project says that the platform should be stationed within a large cylinder with a probability of 99.9% or a small one with a probability of 99%, in order to guarantee the quality of service. The large cylinder is 3km high, with a radius of 4km, which allows the HAP to go upward or downward within a range of 1.5km and shift horizontally within a radius of 4km away from its initial point. The small cylinder is 1km high with a radius of 2.5km.

B. *Geometry of a cell footprint subject to HAP movement*

Any form of mobility can be depicted in 6 degrees of freedom. These possible basic movements can be combined together to constitute any complex movement that a flying object like a HAP can be subjected to.

1) *Shift movements with respect to x, y-axis*

Shift along horizontal direction can be decomposed into movements along x and y-axis in a HAP scenario in order to simplify the analysis. For the reason that the movements along x and y-axis are similarly performed on the same plane, it is possible to merely analyze the effect of shift movement along x direction. If no steerable antenna correction mechanism is employed, movements of these forms will shift all the cells in the service area with the HAP in the same direction. Meanwhile, the shape and size of the cells will remain the same. Namely, after the movement,

$$x_{cell\_new} = x_{cell\_previous} + x_{hap\_shift} \tag{1}$$

$$y_{cell\_new} = y_{cell\_previous} + y_{hap\_shift} \tag{2}$$

$x_{cell\_previous}$, $y_{cell\_previous}$ are the previous positions of a cell along x-axis and y-axis respectively, x_{cell_new} and y_{cell_new} denote the new positions of the cell along x-axis and y-axis respectively after the HAP shifts horizontally. x_{hap_shift} and y_{hap_shift} represent the distance between the previous and new position the HAP shifts along x and y-axis. Here, the dotted lines represent the original position of the cells, while the solid lines are the ones after the movement.

2) Shift movement with respect to z-axis

Movement along z-axis will cause expansion or contraction of the size of the cells, and therefore the whole service area. If the HAP moves upward, the central point of each cell will move away from the Sub Platform Point (SPP), and the size of the cells will enlarge correspondingly. Here, the centre of a cell is defined as the point where the boresight of the antenna intersects the Earth's surface. Conversely, it is expected that when the HAP moves downwards, the central point of each cell will move towards the SPP, with the size of the cells shrunk. That is because the elevation angle of the antennas located on the HAP is constant while the height of the HAP is changed, which leads to proportional expansion or contraction with respect to the previous and new z-position.

$$\text{Height ratio} = \frac{z_{hap\_new}}{z_{hap\_previous}} = \frac{x_{cell\_new}}{x_{cell\_previous}} = \frac{y_{cell\_new}}{y_{cell\_previous}} \tag{3}$$

Where $z_{hap\_previous}$ and z_{hap_new} are z-positions of the HAP before and after the shift.

3) Yaw

In the case of yaw, the HAP rotates with respect to the z-axis, the rotational angle could vary from 0 to 360 degrees. As a result, the position of the cells will move in a predictable circular manner around the SPP point of the same rotational angle with the HAP, but the size and shape of the cells remain the same. Provided the HAP rotates $\Delta\theta$ degrees, and the previous angle of a cell with respect to x-axis is θ (See Fig 2), which can be given by

$$\theta = \arctan\left(\frac{y_{cell\_previous}}{x_{cell\_previous}}\right) \tag{4}$$

Then the position of the cell after the HAP yaws can be calculated as follow

$$x_{cell\_new} = d\cos(\theta + \Delta\theta) \tag{5}$$

$$y_{cell\_new} = d\sin(\theta + \Delta\theta) \tag{6}$$

Where d is the distance between centres of two cells.

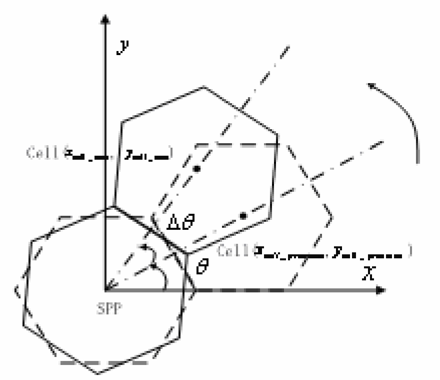

Fig. 2 Modelling the movement of a cell centre with respect to yaw

4) Pitch and roll

Compared with yaw, the location of the cells in the situation of pitch and roll are of more complexity to analyze. The difference between modeling the two movements lies in the axis around which the HAP rotates: roll is rotation with respect to y-axis, while pitch is rotation with respect to x-axis. For the reason that rotation is performed on two axis lying in the same plane, the two movements have similar effects on the ground. Therefore, this work takes roll for example to analyze the effect of the movements[4]. When the roll angle of a HAP changes $\Delta\varphi$ (See Fig. 3), an antenna boresight's trajectory describes a circular curve which yields displacements of the cell centre in a hyperbolic manner. In this scenario, the boresight of the antenna passes through point p on that circular curve parallel to x-z plane and centred with the point $(0, y_a, z_{hap})$, so that the footprint a that the boresight intersects the ground moves to a'. Here, the roll angle φ and the roll radius r_c can be easily calculated as follows

$$\varphi = \arctan\frac{x_a}{h} \tag{7}$$

$$r_c = \frac{h}{\cos\varphi} \tag{8}$$

The coordinates of point p are

$$x_p = r_c\sin(\varphi + \Delta\varphi) \tag{9}$$

$$y_p = y_a \tag{10}$$

$$z_p = h\left[1 - \frac{\cos(\varphi + \Delta\varphi)}{\cos\varphi}\right] \tag{11}$$

Then, according to the geometrical relations, the coordinates of footprint a' after roll are

$$x_a' = \frac{x_p h}{h - z_p} \tag{12}$$

$$y_a' = \frac{y_p h}{h - z_p} \tag{13}$$

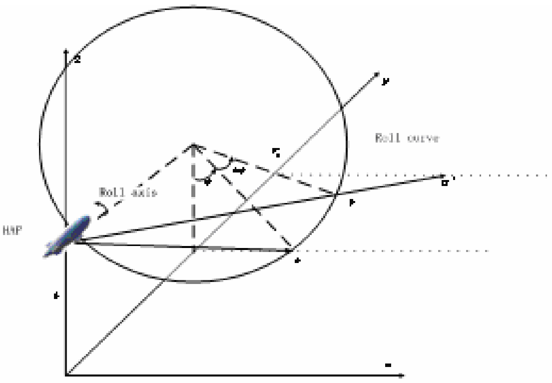

Fig 3 Illustration for the change in antenna pointing angles with respect to roll

Movement of this form will have significant impact on the cells far from the SPP point, especially when the roll angle is large. The movement causes the distortion of nearly all the cells' shape, and therefore the entire coverage area.

III. HAP MOVEMENT CORRECTION MECHANISM BASED ON STEERABLE ANTENNAS

It has been shown in part II that HAP movement can change the coverage area and therefore the quality of service, because certain part of the coverage area might be left with no service. Employing steerable antennas are considered to be an effective way in designing the HAP payload to cope with this problem. When the HAP performs movement, the elevation of the steerable antennas can be dynamically modulated to different directions to recover original cellular architecture on the ground as much as possible. Here, a practical steerable antenna correction mechanism is proposed. In this mechanism, the antennas are controlled in groups, which not only compensate the undesirable effect of HAP movement to certain degree, but also simplify the equipment.

1) Steerable antenna correction mechanism for shift movement with respect to x and y-axis

When HAP shifts horizontally, centre cell correlation mechanism can be adopted, namely, the antenna of the centre cell is always pointing to the centre of the coverage area, and all the antennas are interconnected with each other. Therefore, if the HAP shifts d km, the antenna pointing angle should change $\Delta\varphi$ to guarantee constant coverage (See Fig. 4). The value of $\Delta\varphi$ is given below [5]

$$\Delta\varphi = \arctan\frac{d}{h} \qquad (14)$$

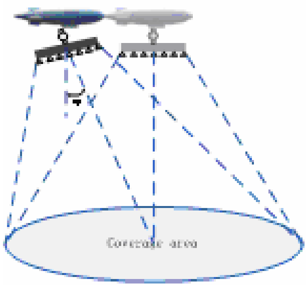

Fig. 4steerable antenna correction mechanism for horizontal shift movement

2) Steerable antenna correction mechanism for shift movement with respect to z-axis

When the HAP shifts along z-axis which leads to expansion or contraction of cells, the mechanism given by Fig. 5 can be adopted to modulate the steerable antennas[6]. In this mechanism, the antennas are interconnected with each other by groups. A group consists of a ring of antennas whose elevation angles are the same and coverage area are of the same distance from the SPP point. So the antennas of a certain ring will symmetrically change their pointing angle together, while the central antenna remains the same.

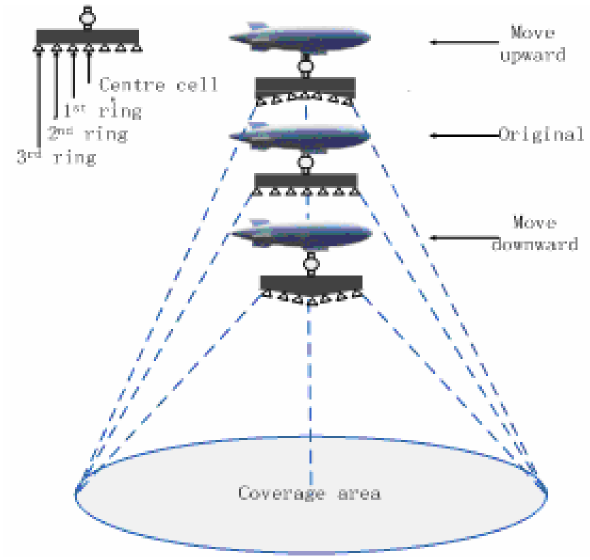

Fig. 5 Steerable antenna correction mechanism for shift movement with respect to z-axis

When the HAP moves downward, the antennas of the first to the Nth ring will be pushed outward, and the one pointing to the centre will move a little downward. Rational adjustment can make all the antennas pointing to the original position on the ground, but the elevation angle is different from the original angle. As for the situation that the HAP moves upward, the mechanism is quite the reverse. The antennas of the rings will be dragged inward, and the centre cell antenna will move slightly upward. Moreover, the antenna of the centre cell should dynamically modulate its beamwidth according to the HAP's height to avoid expansion or contraction of the centre cell.

3) Steerable antenna correction mechanism for pitch

In this case, although the coverage area rotates with respect to the SPP point, quality of service of the entire coverage area is not affected. Therefore, the steerable antennas are not necessary to be modulated.

4) Steerable antenna correction mechanism for roll and pitch

In the two cases, the SPP point under HAP is constant, but all the antennas point to a different direction. The HAP can modulate the elevation angle of the steerable antennas by using the mechanism given in Fig. 6. This mechanism allows the antennas to point to the original position of the cells and keeps the elevation angle of the antennas constant. Therefore, the roll and pitch movement will not affect the quality of service in the coverage area if such mechanism is adopted.

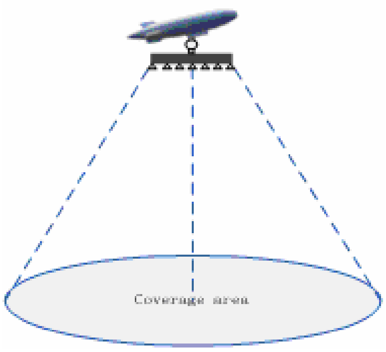

Fig. 6 Steerable antenna correction mechanism for roll and pitch

Hence, six basic movements can be compensated by adding payload for antenna pointing angle correction. In order to rationally cope with complex movement consisted by the 6 degrees of freedom, the steerable antenna system should be of great adaptability and intellectuality. The mechanism guarantees that the HAP can still provide constant coverage to an area after undesirable movement.

IV. CALCULATION OF CARRIER TO INTERFERENCE RATIO

The CIR (Carrier to Interference Ratio) determines the modulation and coding schemes that can be used. The higher the CIR level is the higher the data rate that can be accommodated. Therefore, to analyze the CIR level in the coverage area is of significant meaning.

When sidelobe levels are very low, the peak directivity is often approximated by [7]

$$D_{\max} = \frac{32\ln 2}{\{2\arccos(\sqrt[n_\theta]{\frac{1}{2}})\}^2 + \{2\arccos(\sqrt[n_\varphi]{\frac{1}{2}})\}^2} \quad (15)$$

Where n_θ and n_φ are the indices for optimising directivity at the cell edges. Both are functions of the antenna 3dB beamwidths. Hence, the directivity of certain position can be calculated as

$$D = D_{\max}\{\cos(\theta_{user}\cos(\phi_{user}))\}^{n_\theta}\{\cos(\theta_{user}\sin(\phi_{user}))\}^{n_\varphi} \quad (16)$$

The power level that the users connect to the base station on the HAP is

$$P_{RX} = D\frac{G_{ref}}{d^2} \quad (17)$$

Where d is the distance between the antenna and the user. G_{ref} is reference gain. Thus, the CIR level acquired at a certain position can be calculated as follows

$$CIR = \frac{P_a}{\sum_i P_i - P_a} \quad (18)$$

Here, P_a represents the signal power level that the antenna radiates to this cell. $\sum_i P_i$ represents the sum of all co-channel signal power at this cell.

V. SIMULATION AND RESULTS

The analysis developed in the sections above points out that by employing steerable antennas and payload for attitude control can effectively provide compensation for the HAP movement. In the cases of pitch, roll and yaw, the quality of service can not be affected because of rational steerable antenna correction mechanism. However, when the HAP shift along x, y and z-axis, the CIR level in the coverage area will change, here we are in the position of simulation and analysis of the results. In this work, results for 127 cell architecture are given, choosing a channel reuse number of four.

Fig. 7 illustrates the CIR contours for one channels of four when the HAP is positioned in its intended location. The CIR contours are at 3-dB intervals. Because the HAP is without movement and no antenna correction mechanism is employed, the distribution of the CIR contours is geographically symmetrical. Fig. 8 illustrates the CIR contours when the HAP shifts 2km along x-axis, and centre cell correlation mechanism is adopted. In this case, the CIR contours for the centre cell is of no considerable change, but the CIR pattern for the cells around shows undesirable distortion. The CIR tends to be pushed away from its original location along x-axis; especially the cells in the direction of +x show a fairly severe degradation of CIR coverage and an obvious trend of contraction toward the zero point. While the cells in the direction of –x move far away from the zero point, and the CIR level is slightly higher. This asymmetrical distribution will cause the degradation of quality of service in parts of the coverage area.

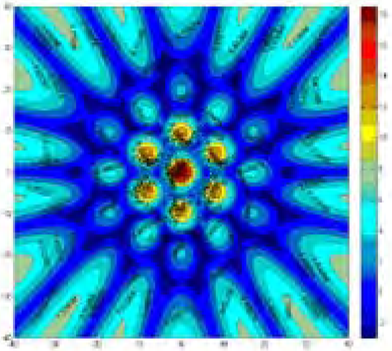

Fig.7 CIR contours for one channel of four without HAP movement

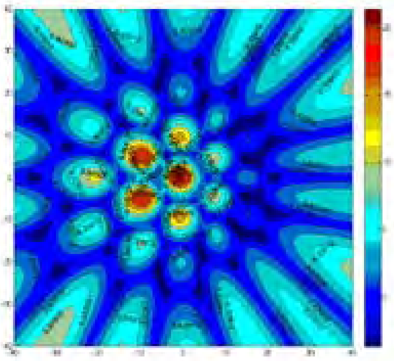

Fig.8 CIR contours for one channel of four when HAP shifts 2km along x-axis and centre cell correlation mechanism is employed

The geographical coverage for 2km HAP movement along x-axis is quantified in Fig. 9 as the fractional area of the co-channel cell group served at a given CIR threshold. Meanwhile, the simulation result when the HAP stays at its intended position is given as a comparison. For the case that the HAP moves 2km without adopting centre cell correlation mechanism, the CIR level in the coverage area is deteriorated, that is, the fractional area served at CIR threshold below 4dB declines. The centre cell correlation mechanism offers a clear advantage in terms of the quality of service, the percentage of coverage area rises under this circumstances.

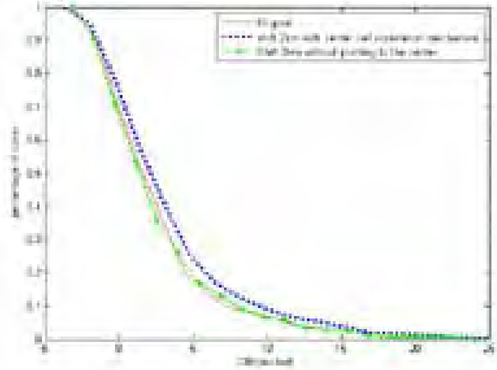

Fig. 9 Coverage for one channel of four when HAP shifts 2km along x-axis and centre cell correlation mechanism is employed

Fig. 10 shows the percentage of coverage area at a given CIR threshold with and without employing steerable antennas respectively when HAP goes down 2km. When the CIR threshold is low, the percentage of coverage area above given CIR threshold is nearly the same in the two cases. However, when the threshold is above 2dB, the percentage of coverage area served at given threshold with the steerable antenna correction mechanism is obvious higher than the percentage without it.

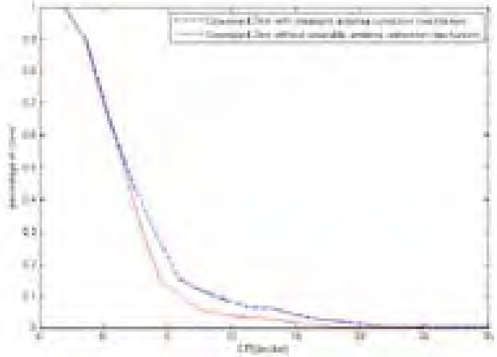

Fig. 10 Coverage for one channel of four when HAP goes down 2km along z-axis with and without employing the steerable antenna correction mechanism

Fig. 11 gives simulation results for the case when the HAP shifts 2km along z-axis and steerable antenna correction mechanism is employed. From the curve, it can be seen that When the HAP moves upward, the percentage of coverage area served at a given CIR threshold declines, while the percentage of coverage rises if the HAP moves downward, namely, the quality of service tends to be improved.

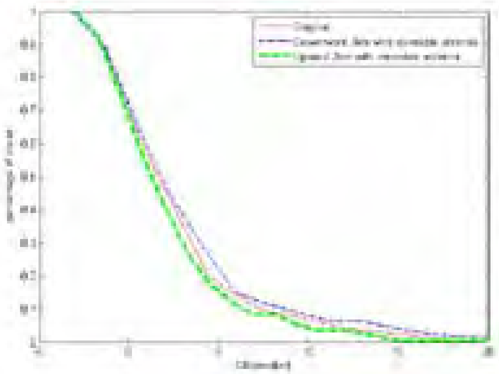

Fig. 11 Percentage of coverage when HAP moves 2km along z-axis

VI. CONCLUSION

Models for predicting the geographical coverage in the cases of shift horizontally and vertically, yaw, roll and pitch of HAP are presented in this work. And also the mechanisms of compensation based on steerable antennas in these cases are explored. Combination of steerable antenna correction mechanism and attitude control system can be well established to compensate HAP movement. However, for the case of HAP shift movement horizontally or vertically, although certain mechanism is employed, the quality of service will still be affected. From the simulation results, it can be seen that when the HAP shifts along x or y-axis, the coverage area moves correspondingly, leaving some part of the area with no effective service. Therefore centre cell correlation mechanism is employed so as to accommodate this movement. However, the entire CIR level in the coverage area is no longer distributed symmetrically, which leads to slightly distortion of quality of service in parts of the coverage area. When the HAP shifts along z-axis, the percentage of coverage area served at a given CIR can be improved to some extent with proposed steerable antenna correction mechanism.

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