Impact of High-Altitude Platforms Rotation on Cellular Mobile Communications

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Abstract: High-Altitude Platforms (HAP) is an emerging technology for mobile broadband communications and is capable of providing many advantages compared to conventional terrestrial and satellite systems. On the other hand, positional instabilities of HAP affect the system performance greatly. In this paper, one of the main problems of HAP positional instabilities, which is the rotation motion, is described and analyzed, and its impact on the handover of cellular systems is also investigated. The total handover due to both user mobility and platform rotational positional instability is discussed and determined. An expression for the number of calls subjected to handover is deduced where it will be a function of users' density and their distribution in the cell, platform angular shift due to rotation, cell geometry, and number of active calling users. The analysis of this number shows the serious effects of the rotational motion instability on the system performance.

Keywords- High-Altitude Platforms; Mobile Communications; Positional Instabilities; Handover.

1. INTRODUCTION

High-altitude platform (HAP) is a new promising technology for providing wireless mobile communications services [1-8]. It is efficient in many terms including system deployment, communications performance and infrastructure cost. The radio coverage characteristics of HAP is superior to both terrestrial and satellite systems due to the capability of line of sight communications as in the satellite systems, but at lower propagation loss due to the relatively lower altitudes (20-60 km). Directing beams toward intended locations is obtained by using either spot beam antennas or a two-dimensional phased array that forms the desired cells on the earth surface. As it is an airborne body, the main problem with platform communications is the station keeping operation needed for proper and stable radio coverage. This in turn requires continuous monitoring for the platform attitude. Providing corrections to the platform attitude consumes part of the power supplied to the platform by the solar panels or fuel cells. As a consequence of this power consumption, the power efficiency is reduced. The attitude instability may be due to horizontal drift, vertical motion, platform inclination, and rotation around its vertical axis due to the change in wind direction. Out of these, the most stringent one is the latter.

The rotation of the platform may have very serious effects on the system performance especially for the outermost-formed cells (i.e. the cells formed by beams of lower elevation angles). This rotational motion can be corrected by re-directing all the beams forming the cells on the ground to cover their correct specified locations mechanically by steering the antennas payload or performing handovers to the mobile users of those moving cells, which on the other hand indicates very large number of handoff calls. Another problem regarding the use of stratospheric platforms in cellular communications is the increased system complexity as it works as a multiple base station unit, therefore, the users location information will be very sensitive to the beam pointing errors resulted from the positional instability of the platform. Therefore, in this paper, we will analyze the handover process due to instability effects especially the rotational motion. The paper is arranged as follows; in section 2, the HAP cell geometry is described. In section 3, the rotational motion of HAP is modelled and section 4 depicts its impact on the system handover. Finally, concluding remarks are dawn in section 5.

2. GEOMETRICAL DESCRIPTION OF HAP CELLS

The HAPs wireless communication system utilizes directional, as well as phased antenna arrays to construct its ground cells [9-13]. Directional antennas may be in the form of spot-beam antennas such as parabolic reflectors, horn antennas, lens antennas which give the desired directional pattern. The use of directional antennas has some advantages such as its practical availability and simplicity but on the other hand a failure in one of them results in a coverage hole due to the absence of the beam used in forming its cell. Ground cells also can be formed by directing a beam using adaptive or phased arrays which has a widespread use [14] where the coverage beam is formed 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. In this paper, we will apply spot-beam antennas to form the ground cells as it is feasibly
realizable and available for many applications and provide less complexity to the system.

Considering a HAP that is located at an altitude about 20 km high, at point $P$ as shown in Fig. 1, where the footprint of a beam formed by any of the mentioned antennas onboard the HAP is shown.

The cell footprint is approximated generally as an ellipsoid with minor axis $HK$ and major axis $EF$.

The minor and major axes will define the cell shape and is defined as in [15] using the curved-earth cellular geometry shown in Fig. 2 where we take into consideration the earth curvature. In this figure, the major axis will be the arc between the two ground central angles $\gamma_1$ and $\gamma_2$ which can be deduced as

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

and

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

where the cell center has a ground center angle given by

$$\gamma_o = \frac{1}{2}(\gamma_1 + \gamma_2)$$

and we can get the distance $PB$ as:

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

and the distance $BC$ will be

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

therefore the platform-to-cell center slant distance will be

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

from the above equations, the cell major axis, $b_c$, can be defined as

$$b_c = EF = R(\gamma_2 - \gamma_1)$$

or

$$b_c = R\left[\sin^{-1}\left(1 + \frac{h}{R}\sin\left(\frac{\theta_o + B_o}{2}\right)\right)\right.
- \sin^{-1}\left(1 + \frac{h}{R}\sin\left(\frac{\theta_o - B_o}{2}\right)\right) - B_o$$

and in this case the value of $\theta_c$ will be

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

or
Therefore the cell minor axis, \( a_c \), will be

\[
a_c = HK = 2PC\tan\left(\frac{B_o}{2}\right)
\]

or

\[
a_c = 2h\sec(\theta_o)\tan\left(\frac{B_o}{2}\right)
\]

which can also be given by

\[
a_c = 2R\tan\left(\frac{B_o}{2}\right)\left(1 + \frac{h}{R} - \frac{1}{2}\left(\cos(\gamma_1) + \cos(\gamma_2)\right)^2 + \frac{1}{4}\left(\cos(\gamma_1) + \cos(\gamma_2)\right)^2 \tan^2(\gamma_o)\right)^{1/2}
\]

Fig. 3 depicts an expected cellular system using 10x10 elements phased antenna array covering an area of radius of about 20 km and the platform is located 20 km high.

3. MODELING OF HAP AXIAL ROTATION

The beam actually has two extreme elevation angles according to its direction. The significant one is the smaller. A user within a cell will be covered between such two elevation angles. The geometry is shown in Fig. 4 where we take the elevation plane \( ocd \), defining the lower elevation angle as \( \alpha \) and the upper one as \( \beta \).

The upper elevation angle \( \beta \) is given by

\[
\beta = 90 - \theta_o - \frac{B_o}{2}
\]

and \( \alpha \) is given by

\[
\alpha = 90 - \theta_o - \frac{B_o}{2}
\]

The two elevation angles are equal when the platform is overhead (i.e. \( \theta_o = 0^\circ \)).

The major challenging factors in the platform communications arise from the positional and attitude instabilities. These problems result mainly from the wind forces and the atmospheric pressure variations at the HAP altitudes. These will force the platform to move from its specified position and results in variations in the cellular radio coverage configurations. These motions include the shift in altitude, horizontal and rotational motions due to the temporarily change in wind direction. We concentrate here on the rotational motion investigating the main resulted problems.

Firstly, we formulate an expression for the cell boundary motion due to this specific shift. This motion can be expressed as the distance the cell boundary moves (\( \Delta c \)), which depends on the elevation angle. As shown in Fig. 5, it may be written as

\[
\Delta c = h\tan(\theta)\Delta\phi
\]

where \( \Delta\phi \) is the spin error angle (rotational error angle).
For any given cell that has a lower and upper elevation angles \((\alpha \text{ and } \beta)\) respectively, this shift in a cell boundary is bounded by

\[
h \cot \alpha \Delta \phi \leq \Delta c \leq h \cot \beta \Delta \phi
\]  

(17)

As depicted from the last equation, this quantity differs as the elevation angle changes and the lower the elevation angle the larger is that distance. This moving cell has a great impact on the handover and location updating rates as will be discussed in the next subsection. Except the central cell (i.e. the cell where the platform is overhead), all other cells will exhibit such shift when the platform rotates. The most affected cells by such angular error are that at the outer tier and all cells within the same tier (i.e. those that have the same value of \(\theta_o\)) will exhibit the same shift in angular distance.

4. IMPACT OF AXIAL ROTATION ON HANDOVER

As depicted in Fig. 6, even a small rotation will greatly affect the system performance especially the handover process. Users at the cell boundaries will be more affected by such instability and may be subjected to frequent handovers. The problem at the outer tier cells is more serious than at the inner ones. This handover is triggered only by the platform instability and there is another user mobility initiated handover, which results from user motion toward another neighboring cell. Therefore, the total handover is estimated as:

\[
\text{HAP Total Handover} = \text{User Initiated Handover} + \text{Instability Initiated Handover}
\]  

(18)

The instability-initiated handover is configured as the users that are handed to another cell and those users, which are handed from another neighboring cells.

Assuming that the user density is characterized in each tier of cells and these users are uniformly distributed within that tier, the platform is rotated by \(\Delta \phi\), therefore the resulted number of handoff calls will be a function of the number of active calling users, the platform rotation shift \(\Delta \phi\), the cell area, and the elevation angles of such tier. Assume that a \(j^{th}\) tier can accommodate certain number of the cells (footprints) denoted by \(M_j\), has a user density of \(D_u\) where a
ratio of $\eta_j$ of them are active and has an inner and outer radii $r_{ij}$ and $r_{2j}$ determined by the elevation angles $\alpha_j$ and $\beta_j$ respectively, then the number of users that undergoes instability handover for that tier, $N_j$, can be written as

$$N_j = \frac{\Delta \phi}{2\pi} \frac{\pi}{M_j} D_u \eta_j$$

(19)

or

$$N_j = \frac{\Delta \phi}{2} D_u h^2 \eta_j M_j \left( \cotan^2(\alpha_j) - \cotan^2(\beta_j) \right)$$

(20)

If there are $T$ tiers in the system, the total instability handoff users, $N_T$, will be

$$N_T = \sum_{j=1}^{T} N_j$$

(21)

Besides these assumptions we must include another population mapping factor that signifies the user distribution profile within the tier which may be characterized by tier terrain features, users grouping, trading centers, highways...etc. Denoting that factor by $\sigma_j$, so the final number of instability initiated handovers of a tier will be

$$N_j = \frac{\Delta \phi}{2} D_u h^2 \eta_j \sigma_j \left( \cotan^2(\alpha_j) - \cotan^2(\beta_j) \right)$$

(22)

where the mentioned parameters in Eq. (22) are for such tier. A major problem occurs when the rotation angle reaches the azimuthal beamwidth ($B_\phi$), at which all the cell users perform handover and consequently all the users in the corresponding tier will do that. In addition, the other tiers will be subjected to handovers depending on the corresponding cells beamwidths. A multiple handover will occur if the platform rotates by an angle which is a multiple of the azimuthal beamwidth. A useful study of Eq. (22) is obtained if we consider the variation of $N_j$ with the rotation angle $\Delta \phi$. We first determine the number of cells formed in each tier and the directions of beams forming these cells. In Fig. 7 we normalized $N_j$ with $D_u \eta_j$ and we also assume uniform user distribution within the tiers (i.e. $\sigma_j = 1$). As clear from this figure, the number of instability initiated handover users increases as the rotation error angle increases, and also with the decrease in cell elevation angles. The impact of this issue is very important on the system performance. The system complexity increases as one expects such error occurrence at any time and if not managed as required it may cause system failure due to the expected large number of forced terminated calls.

5. Conclusion

Although HAP is considered as a new emerging technology for mobile communications that introduces many advantages compared to both terrestrial and satellite systems, it has potential problems due to positional instabilities that affect greatly the system performance. One of the major drift problems for HAP is the rotational motion due to wind changes. An analysis concerning the effect of rotational motion of the platform on the number of handover calls is performed and an expression for this number is deduced indicating the main parameters controlling it. The analysis has shown that the angular shift even if small becomes more serious when moving to the outer cells as the number of handoff calls increases. The outer cells on the coverage area of the HAP may perform a complete cell handover at rotation angles approaching the azimuthal beamwidth and the whole tier is subjected to all-user-handover making the cellular system to fail.

References


Yasser Albagory: Member of IEEE, B.Sc in Electronic Engineering in 1998 and the M.Sc in adaptive arrays for mobile radio communications in 2002 from the Faculty of Electronic Eng., Egypt. He also has been awarded the Ph.D degree in Communications Engineering in the field of High-Altitude Platform Wireless Communications System in 2008. Now, he is an assistant professor at the Information Technology Department, College of Computers and Information Technology, Taif University, Saudi Arabia. The research interests include adaptive antenna arrays, mobile communications, and high altitude platforms, satellite communications, and digital communications. He is a reviewer of many international conferences and journals in the field of wireless communications and has many journal papers in the area of smart antennas and high-altitude platforms. He is one of the editorial board of the Asian Journal of Technology & Management Research and International Journal of Technology & Management Research. He judges many technical issues regarding the installation of mobile base stations and their effects on the surrounding environment in Egypt. In addition, he is an author of two books in the field of high-altitude platforms and their role in cellular communications issued in 2013 and coauthor of the book “Internet of Things” 2014.