Investigating the effect of High-altitude Platform Positioning on Latency and Coverage of 4G Cellular Systems

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***Abstract*:** Wireless communication technologies are rapidly being adopted and developed by countries all over the world as a strategy for sustaining a digital economy. This has proven very useful for economic recovery from the crises brought about by the COVID-19 pandemic of the year 2020. The latency and coverage area of a wireless network are two major areas that are always seeking improvement. The High-Altitude Platform communication technology can provide improvement in speed and coverage area for 4G cellular systems. This work investigated the effect of positioning High Altitude Platforms on the latency and coverage of 4G cellular Systems. A quantitative approach was used in the methodology of this paper. A HAP model showing a single platform flying in a circular trajectory over Base Transceiver Stations BTSs and serving as a relay mobile station was presented. A detailed simulation algorithm for the HAP and results for the simulation were given. Results showed that using the HAP as a relay mobile station in a network can give a latency reduction of up to 58.9%. Also, the altitude of the HAP directly affects the angle of reception which was found to improve the coverage.

***Keywords*:** Aerial vehicle, Cellular network, Signal delay, wireless network, High Altitude Platform, mobile station.

1. Introduction

Wireless communication plays an invaluable role in sustaining a digital economy. With the emergence of the COVID-19 pandemic in the year, 2020, countries all over the world have suffered a health and economic crisis during the pandemic. According to a recent article on wireless communication [1], Digital technologies have been an effective tool in battling this crisis. Since digital technologies rely on wireless communication one way or the other, the development of wireless technologies will be useful in and post-pandemic era. An emerging wireless communication technology with growth potential is the High Altitude Platform (HAP).

The HAP technology utilizes aerial vehicles positioned in the stratosphere for long-distance wireless communication. The most accepted definition of a HAP as shown in the works of [2]-[4] describes HAP as an aerial platform positioned at the lower part of the stratosphere. Structurally, The HAP can be an airship, balloon or, airplane utilized for telecommunication [2]. Depending on the mechanism employed for flight, it can be aerostatic or aerodynamic. It is also either manned or unmanned but recent technologies in aerial vehicle development are centered on unmanned aircraft [4], [5]. The HAP as a platform for providing wireless communication has numerous advantages over the existing grounded terrestrial and satellite technology as described in [6]. It covers a larger coverage area with low shadowing and, line of sight within its footprint as compared to terrestrial systems. It also has a low signal propagation delay and low cost of deployment and maintenance as compared to satellite systems.

This paper investigates the effect of HAP positioning on latency and coverage of 4G cellular systems. The methodology followed a quantitative approach. The time delay for signal transmission in the HAP/Terrestrial network scenario and that of the terrestrial network alone was tested using computer simulation. A comparison was made between the two scenarios. The magnitude of the received signal strength at the grounded Base Transceiver Stations (BTSs) was obtained via simulation and an analysis of the HAP coverage was made. The system was modeled for a network of HAP/Terrestrial BTS complementing each other to provide coverage to remote locations. Rather than maintaining a hexagonal cell network of BTS linking to a core network from a remote location, the HAP was simply used to bridge the gap in the network. This happens to be more cost-effective for the service providers. The HAPs positioning in the stratosphere offers it a line of sight to BTSs It is also much closer to the BTSs than satellite systems, and hence, long-distance communication is expected to be faster through the HAP. The significance of this study can be seen both in the economic aspect as a cost-saving scheme to bypass land acquisition, construction, and maintenance of radio masts, and environmental aspect as a means to reduce air pollution by eliminating the accompanying exhaust fumes from generators that power these radio masts. In the aspect of security, terrorists have been known to attack and damage terrestrial systems to cripple communication when operating. A HAP solution that passes over terror regions will aid in providing a link to core networks and hence, solve this problem.

The organization of the work is as follows; section 2 gives a literature review on HAP technology and state of art. Section 3 shows the methodology with the system model and simulations. Results and discussion of the result are presented in section 4 and finally, a conclusion is drawn in section 5.

2. Literature review

Projects on HAP flight testing and station keeping has been embarked on in previous years and is expected to continue based on the prospects of the technology. Among the earliest was the HeliNet project in 2001 [7]. It involved the development of an unmanned solar-powered aircraft having a 70m wings span. The purpose of the project was to develop a platform that could deliver broadband communication. The payload limitation of the aircraft made it able to support an upper limit of 121 hexagonal cells at a 60Km diameter coverage area. In 2003, the Optical Communication

Experiment of CAPANINA was initiated [8]. As part of the project, the STROPEX experiment was done aiming at performing measurements on the downlink from a stratospheric platform (22Km altitude) to characterize the channel for high-speed optical free-space communication. The platform used for this experiment were tethered balloons at 400m altitudes for the first trial and 22Km altitude for the second trial with 500mW mean source power, 808nm transmission wavelength and, 8hrs flight duration. The notable conclusion made was the atmospheric attenuation at the right wavelength was below 2dB and that at the wrong wavelength was up to 50dB. The system had a limitation of high attenuation with antenna misalignment. In 2008, project STRATABUS was initiated [9]. It was aimed at reducing the cost of balloon campaigns by managing Long Duration Balloons for housing single or multiple projects sharing the same resource. It had a 100KW power target for 12 days mission duration. In 2013, project Loon was officially announced. It was aimed at providing internet access by utilizing 30 helium balloons forming a network at 20Km altitudes. The platform supported a 100Kg electronic payload, 100W average power per day from solar panels and, an expected flight duration of 100 days. Among the most recent HAP projects currently ongoing is the solar-powered PHASA 35 aircraft having a payload capability of 300 to 1000W steady DC power, 15Kg payload mass and, a1yr flight duration [10]. Another ongoing project is the SCEYE. They developed highly advanced solar-powered airship HAP for delivery of high-speed internet [11]. The advancement seen in recent platform development in terms of flight duration and power storage is encouraging for the technology but there is still a lot more work to be done especially in terms of payload carrying capability of platforms.

The HAP communication channel has been investigated by researchers to obtain suitable channel models for this emerging technology. The latest World Radio Communication Conference (WRC-19) held at Sharm EL-sheikh Egypt 2019 went over the spectrum allocation for the HAP communication channel [12]. The 47/48GHz and 38/39.5GHz allocated globally having 300MHz in UL and DL. The 21.4-22GHz and 24.25-25.25GHz are allocated for region 2 DL. The 6.5-6.6GHz and 31/28GHz are allocated to regions 1 and 3. And finally, the 2.1GHz IMT 2000 band for regions 1 and 3 and some part of region 2. The work by [13] shows how uplink LTE users can use SC-FDMA technology for communicating with the HAP. The paper shows how the user’s elevation angle has a major effect on channel estimation for the LTE SC-FDMA performance. They also show how the channel performance can be enhanced by compensating channel bandwidth, changing the modulation type and, limiting vehicular speed to limit the effect of Doppler. The work by Yong Yang in [14] classifies HAP channel models into three categories, first is the strictly statistic-based models which follow the ITU-R recommendation. They define three types of channel states based on the semi-Markovian process (Line of sight, slight shadowing, and total obstruction). The second category is the GBSB model based on the spacial scatterer density function. The third category is the k-model based on two ray ground reflection model characterized by a Racean factor k. The majority of the research on HAP channels is lacking practical results as HAP implementation for communication is still underway, hence a perfect channel model categorizing HAP communication is yet to be actualized.

The antenna power roll-off as described in the work of [15] shows how the signal power radiated by antenna drops or decays with distance. The work shows how in a practical sense, the spot beam or power radiated from an antenna is not uniform across a designated cell but either falls outside the cell or does not cover the entirety of the cell depending on the rate of power roll-off. The work further shows how the rate of power roll-off from antennas mounted on HAP for communication purposes is dependent on the directivity (main lobe width). They propose that antennas for these kinds of applications should be aperture types with steep roll-off on main lobes and suppressed side lobes. The work of [16] investigates the impact of power roll-off on the performance of a 3G communication system from HAP. The paper shows how the most important factor to consider in designing a 3G system with HAP is the main lobe roll-off and beam shape. They concluded that 10-35dB roll-off is required to achieve optimal capacity. They also concluded that although elliptical beam antennas is the best solution for hexagonal cell, the circular beam antennas with gain adjusted to reduce overlap can also serve. The work by Kayode in [17] shows an analysis of capacity and coverage for a HAP equipped with directional antenna arrays for providing broadband services. A clustering algorithm used to determine cluster heads using realistic vehicle mobility traces was presented. They concluded that a fewer number of active users per cluster can be achieved by increasing the number of clusters and hence making it easier to direct a fixed number of the beam on the user. It was also concluded that for a 900 antenna element configuration, a minimum of 20 clusters will be required to achieve 95% coverage. The work by Steve C in [18] proposes a beam pointing algorithm from HAP for coverage with an extended service area. The algorithm was studied over a 60km service area utilizing a planer antenna array. The result showed that users achieved a CINR improvement of 5-15dB than other schemes. The main contribution of the work was the compensation for beam broadening at low elevation angles which introduce cell overlap when left unchecked.

From the literature review presented, a lot of research has been done ranging from flight testing to channel estimation and finally antenna configurations. With the timing of the early emergence of the HAP concept and the spectrum allocation by ITU on the IMT 2000 band (3G cellular technology). Most of the research work on antenna configuration reviewed focused on interference control and capacity improvement for HAP with 3G technology. The research centered mostly on HAP as an alternative to terrestrial systems in rural areas. The other possible use of HAP mainly as a complementary technology and as a relay for terrestrial systems is yet to be fully explored from my observation. This work aims to breach that gap.

3. Research method

To investigate the effect of positioning of the HAP on latency and coverage, a quantitative approach was used in the methodology of this paper. The aim was to find out how long it takes for a signal to be transmitted via the HAP and at what signal strength is the retransmitted signal received from HAP at cell edges. This will give an understanding of the latency in signal transmission and the coverage area of the HAP at different positioning. To achieve this aim, the research was divided into 3 steps.

First, we give the HAP model, channel model, and antenna model.
The second, is the simulation of the model.
Third, is the analysis of simulation results to meet the research aim.

The remaining part of the methodology will discuss these 3 steps and what was achieved during this research.

3.1 HAP model

The HAP scenario for this study is a single platform acting as a relay station linking multiple earth terrestrial BTS to a core network. This is shown in Figure 1. Both the BTS and core network, therefore, lies within the footprint of the HAP. The BTS antennas are fixed while the HAP is fitted with an array of directional antennas with beam steering to focus on its footprint. The BTSs are assumed to communicate with the end-users.

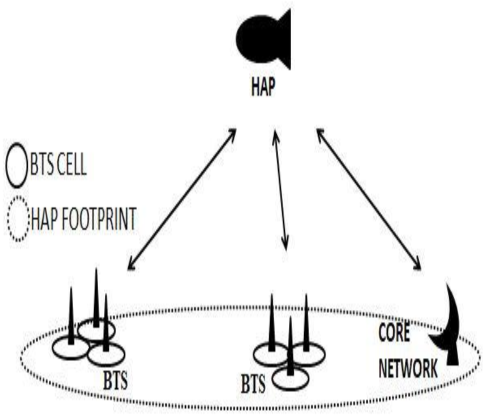

Figure 1. HAP model

Unlike most HAP models from previous research where the HAP directly serves end-users in a limited coverage area of 30 km, we propose to have the HAP serving BTSs and the BTSs serving end-users. The benefit of this model can be seen as the HAP will have a much wider coverage since both the HAP and BTSs have a high gain antenna for long-distance signal transmission and reception. To test the model in Figure 1, the effects of the positioning of the HAP over its footprint were studied by varying its altitude and radius of trajectory as shown in Figure 2 and Figure 3.

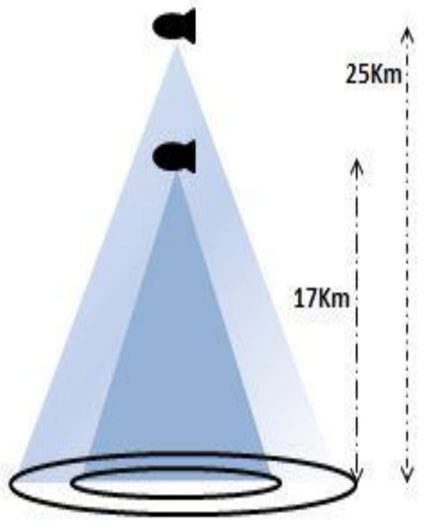

Figure 2. Change in Altitude Positioning

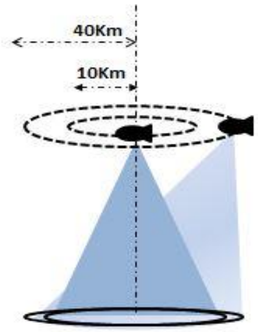

Figure 3: Change in the radius of trajectory

3.2 Channel model

The Free Space Loss Model (FSL) is our assumed channel model. Analytic channel models such as the Semi-Markovian process-based model, and that of the racian distribution factor model have been used for other HAP-related research [15]. The empirical channel models like the Okumura-Hata models which are carried out with simulation of randomly generated urban environments to account for the effect of shadowing in densely populated urban areas have also been used for other HAP research [2]. But since our BTSs antennas are mounted high on radio mast above ground obstructions and shadowing, the effect of shadowing is assumed to be negligible. The channel is assumed for a clear sky with low humidity and hence very little atmospheric attenuation. The FSL model although very optimistic but would still give a close description of the channel of our assumed system model. Equation (1) shows the FSL model.

$$L_{fsl} = 20\log(f) + 20\log(d) + 92.4 \quad (1)$$

From equation (1), f is the carrier frequency in GHz and d is the distance between the Haps and the BTS in km.

3.3 Antenna model

With the high altitude of the HAP, the types of antennas that can be used to focus on its target area are those of high directivity. Aperture antennas of high directivity and suppressed side-lobe levels are assumed for the HAP. The radiated power is concentrated on the antenna main lobe with suppressed side-lobe levels. The directivity D of such antennas as described in [19] can be approximated as shown in equation (2).

$$D = D_{max}(\cos\theta)^{n} \quad (2)$$

From (2), θ is the angle to boresight in degrees, n is the roll-off factor and Dmax is the maximum directivity in dB.
The slant distance between the HAP and each BTS within its coverage area is an important parameter that will be used to analyze both the coverage and latency of the HAP signal. This is given in equation (3).

$$d = \sqrt{(x2 - x1)^2 + (y2 - y1)^2 + (h2 - h1)^2} \quad (3)$$

From equation (3), d is the Euclidean distance between the HAP and each BTS in km. Where x, y, and h are the 3-coordinates. Following this is the equation for the angle to boresight.

$$\theta = \arccos(20/d) \quad (4)$$

Equation (4) shows θ as the angle to boresight in degrees between the HAP and BTSs. d is the slant distance from equation (3). From angle to boresight θ, the directivity D is given in equation (5).

$$D = \frac{72815}{2\left[2\arccos\left(\sqrt[n]{1/2}\right)\right]^2}(\cos\theta)^n \quad (5)$$

Equation (5) is the expanded form of equation (2) which gives the directivity in dB of the HAP antenna. n is the roll-off factor and θ is the angle to boresight. This in turn is used to calculate the Gain Gt of the transmitting antenna as shown in equation (6).

$$Gt = \eta D \quad (6)$$

Equation (6) shows the HAP transmit antenna gain in dB and η stands for the efficiency of the antenna and D is the directivity. Finally, the received power at receiving antenna is calculated with the formula as given in equation (7).

$$Prx = Pt + Gt + Gr - L \quad (7)$$

Equation (7) shows received power Prx at BTSs in dBm. Pt is the transmit power of the antenna, Gr is the receive antenna gain and L, the sum channel losses, is given in equation (1).

To find out the effect of positioning on latency, since microwaves are known to travel at the speed of light, the velocity formula was used as given in (8).

$$velocity = \frac{distance}{time} \quad (8)$$

The distance is in km and time in seconds.

3.4 Simulation procedure

The MATLAB R2016a simulation software tool was used for the simulation. The parameters of the simulation are given in Table 1.

Table1. Algorithm used for Simulation

Parameter	Value
Transmit Power of Hap	34dBm
Carrier Frequency	3.5Ghz
Receiver Antenna Gain	37dBi
Hap Altitude	(17, 22, 25)Km
Roll-off factor n	5
Antenna Efficiency	0.75

Using the parameters listed in Table 1, Lines of codes were run on the MATLAB simulation editor and the algorithm used for the simulation is given in Table 2.

Table 2. The algorithm used for Simulation

Algorithm 1: HAP Simulation Pseudocode

```
1   x[ ]   ←   set values of x coordinate
2   y[ ]   ←   set values of y coordinate
3   h[ ]   ←   set values of z coordinate
    // begin first loop for N number of HAP  positioning on its trajectory
4   for i = 1 : N do
5     for j = 1 : N 2 do        // Set j size N2 for cell array (j x k)
6       for k = 1 : N3 do   // Set k size N3  for cell array (j x k)
7         d [ ] ← equation (3)     //solve for distance
8         θ [ ] ← equation (4)     //solve for angle
9         D [ ] ← equation (5)     //solve for Directivity
10        g [ ] ← equation (6)     //solve for gain
11        l [ ] ← equation (1)     //solve for  loses
12        p[ ]← equation (7)       //solve for received power
13      end
14    end
15 end
```

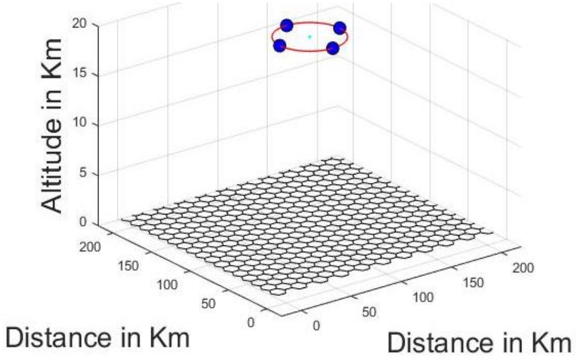

Figure 4: HAP and BTS on 3D plane

From the algorithm in Table 2 numbers 1-3, the HAP and BTSs coordinates are assigned in the x, y, and z planes. They are obtained using a graphical approach. Hexagonal cells are drawn to represent the BTS locations in the 3D plane and the HAP is located at an elevation on the z plane. This is shown in Figure 4. Each BTS was assumed to be a macro cell of radius 3 km and full loading of BTSs was assumed over a (200 km x 200 km) coverage area.

The first loop from Algorithm 1 number 4 assigns N number of positions for taking readings on the trajectory of the HAP (azimuth). These positions are for pi/2, pi, 3pi/2, and 2pi. These positions are shown in Figure 5, in a 2-dimensional top view.

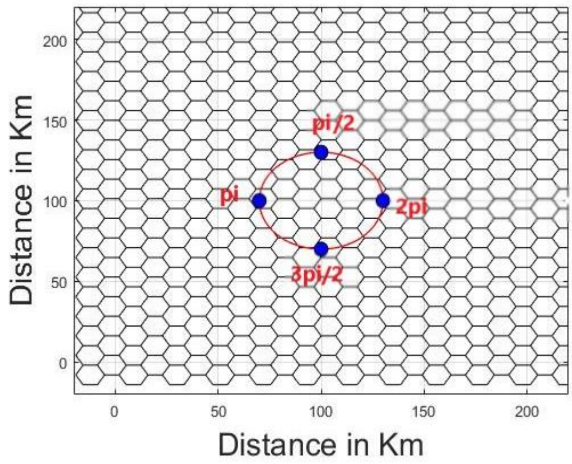

Figure 5: HAP and BTS on 2D plane

The second and third loops from Algorithm 1, numbers 5 and 6 sets J by K cell array size (j x k) for the BTS. Finally, the parameters are computed within the last loop and their equations are as given in equations 3-7.

4. Results and discussions

The first part of the result shows the effect of positioning of the HAP on varying radius of trajectory along its horizontal path. Since the HAP is modeled to be moving along a circular path, this part of the result shows how the distance and angle to boresight to each BTS changes with HAP movement as shown in Figure 6.

Figure 6 shows plots of distance and angle to boresight of each BTS as the HAP moves to 4 different positions. Notice how the reception angle changes at different HAP positioning along the azimuth as indicated by different colors (green, black, red, and green). Setting a 30 km trajectory for the HAP shows that, the reception will be poor at certain positions. This is due to the angle of reception diverging with increasing distance. When the radius of trajectory is reduced as shown in Figure 7, the reception angle and distance converge

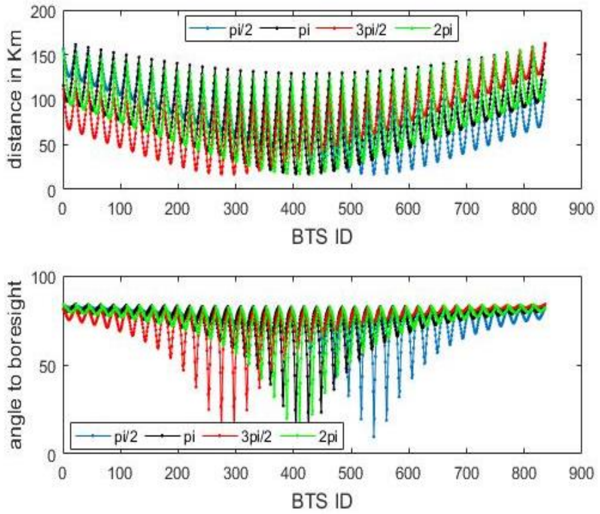

Figure 6: Effect of 30km HAP trajectory on reception angle and distance.

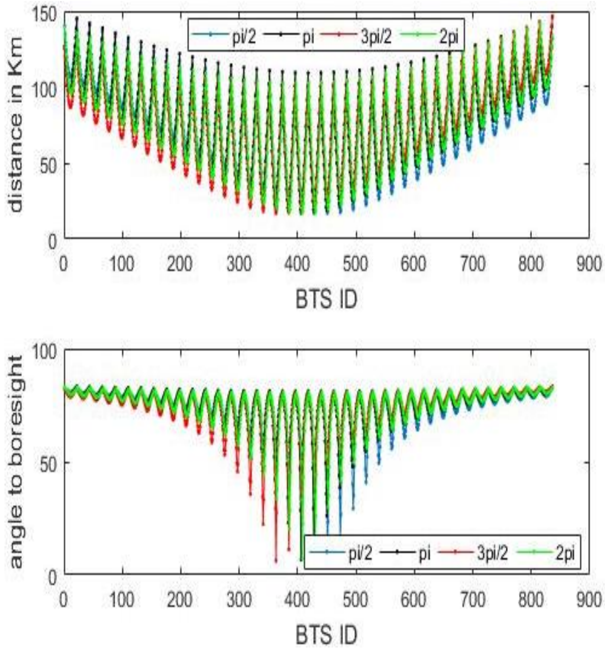

Figure 7: 10Km radius of HAP trajectory

From Figure 7, notice how as the radius of trajectory is reduced to 10 km, the angle of reception at different positioning of the HAP shows a minimal change in value. This shows that having a reduced trajectory path for the HAP will have little effect on angles of reception at BTS.

The second part of the result shows the effect of using the HAP on the signal latency. Since the HAP is modeled to complement terrestrial systems, this part of the result shows just how much signal propagation time is saved by utilizing the HAP as a relay station. This is given in Figure 8.

Notice how steep the rise in latency for the terrestrial BTSs network is as compared to that of the HAP network. By calculating the percentage reduction in latency between the HAP scenario and terrestrial network scenario from Figure 8, the average reduction in latency between the two scenarios was calculated to be 58.9%. This shows that using the HAP as a relay station can reduce signal propagation time by up to 58.9% in a wireless communication link.

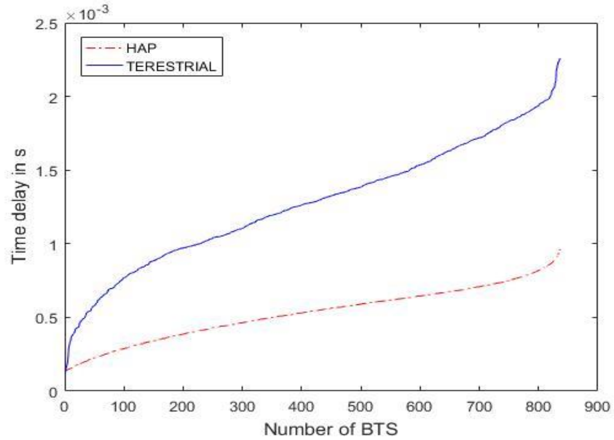

Figure 8: Effect of Positioning of HAP on Latency

The last part of the result shows a summary of the coverage at different HAP positioning. This is given in Figure 9.

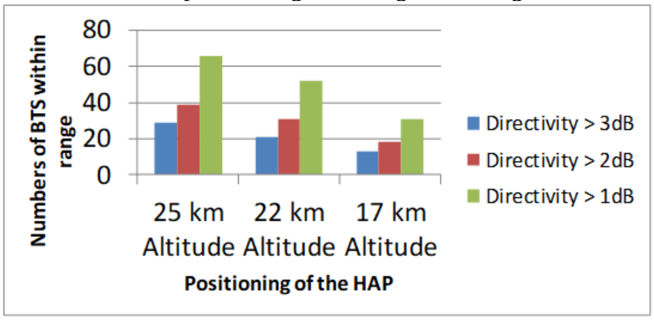

Figure 9: Effect of HAP positioning on

Notice that when the HAP is at an altitude of 25 km, 65 of the BTSs are within its coverage area. While at a reduced altitude of 17 km, 35 of the BTS are within range. Since coverage is improved at a higher altitude, it can be deduced that reception angle is better at higher altitude for HAPs.

5. Conclusion

In this work, the effect of the HAP positioning on latency and coverage area was investigated. A simulation algorithm was given for the hybrid HAP/Terrestrial network and simulation results were presented. It has been shown that positioning the HAP to move at a high radius of trajectory will result in poor signal reception at some areas within the footprint. The HAP will therefore perform better at a reduced radius of trajectory. It has also been shown that using the HAP as a relay station to link BTSs to a core network in a hybrid topology can give a reduced latency of up to 58.9% as compared to a terrestrial network of BTSs alone. It has also been shown that the altitude of the HAP determines the reception angle and higher altitude positioning gives a better angle of reception at grounded BTSs. It, therefore means that positioning the HAP at higher altitudes significantly increases the coverage area of the HAP. The work does not investigate spectrum sharing and access techniques for the HAP and thus, the capacity of the HAP architecture was not addressed. Future research direction can be aimed at finding the effect of modulation and access techniques on the capacity of the system.

6. Acknowledgement

This research is fully funded by Nigerian Communication Commission (NCC) through the R&D unit. We would like to thank the research and development unit of the NCC for monitoring and funding this research.

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