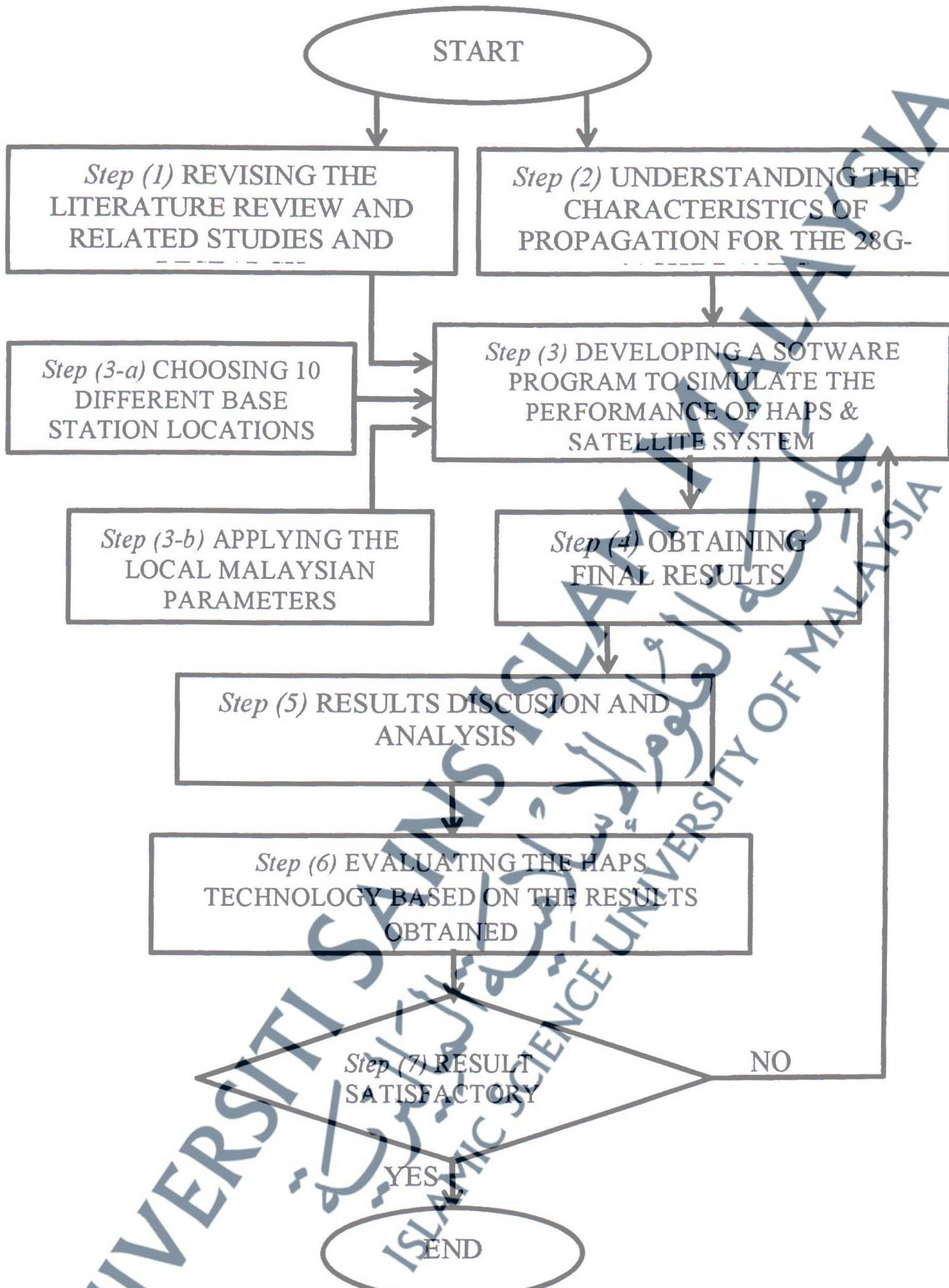
CHAPTER III: METHODOLOGY

3.1 Introduction

The purpose of this chapter is to describe the technique used in this thesis, which contains the tasks, procedures, details about how the study was carried out, and the steps conducted to achieve the specified objectives. The investigation of HAPS signal and the channel modeling will be highlighted as well as the analysis of the HAPS link design. The diversity techniques were also included in this chapter to mitigate the attenuation produced by rain. The main goal of analyzing the attenuation is to design the HAPS link budget as well as to identify the best place for the HAPS to be located in the peninsular of Malaysia.

The rain attenuation is dominant for HAPS links. Therefore, it is considered as the most important issue. This study focuses on this type of the signal propagation impairment source, while neglecting the others whose impact is much lower relatively. The efforts were exerted to achieve the objectives of this work, starting from collecting the related data such as the geographical location properties of the stations of interest in Malaysia, in terms of their longitude and latitude, rainfall rate statistical data over a long-period as well as the earth station's height. The rain data has been collected from the Malaysian Metrological Department (MMD). Chebil model was used to convert the rainfall data from mm to mm/h. The equations related to the HAPS signal impairments have been studied and all the related parameters were understood. Thus, accurate calculations were conducted for the intended purpose in this thesis.

Figure 3.1: Methodology flow chart



The methodology strategy which has adopted to accomplish this study is as follows: A total of 10 different locations were selected based on the highest rain intensities. Each location has different geographical characteristics such as the base station altitude above sea level, the location in terms of longitude and latitude, and the annual rainfall rate which plays the main role in the attenuation caused by the rain. Two HAPS located at an altitude of 25 km were needed to cover the whole peninsular Malaysia without any restrictions. These measurements were based on the recommendations of the international communication union regarding HAPS technology.

The numeric data of the geographical location (longitudes and latitudes) of this study were calculated using Google Earth application while rainfall rate data of peninsular Malaysia were obtained from the Malaysia Meteorological Office (MMO).

The specific rain attenuation impairs the HAPS earth-space link of the selected earth stations will be predicted and analyzed with respect to the rainfall rate statistics data, signal polarization, and the elevation angle.

The total attenuation due to the rain will be calculated based on a modified ITU-R model, with respect to the operating frequency of the HAPS (28-31 GHz) and the earth station longitude and latitude, assuming that the received signal is circular polarized at once, then in vertical and horizontal polarities.

The modified model that is able to predict the earth-space rain attenuation when the signal path is either completely or partially affected by the rain will be presented. It is based on the empirical model of the international telecommunication union. The model was tested against the ITU-R model. The prediction mechanism of this model is to predict the attenuation of the entire signal path, and then subtracts it from the unaffected path attenuation to obtain the rain attenuation of the affected signal path.

The second model that has been developed to predict the rain attenuation is dedicated to the non-stationary satellites such as, Medium Earth Orbit (MEO) and Low Earth Orbit (LEO). The model utilizes the reduction factor based on ITU-R rain attenuation model. Attenuation prediction using this model requires the knowledge of some parameters such as rainfall rate statistics data, the velocity of both the satellite and the clouds, and the rain cell size.

Another model was used to predict the specific attenuation of rain based on the knowledge of rain microstructure parameters such as the rainfall rate and the size distribution of the raindrops. The drop size distribution was calculated based on the Marshall-Palmer model, while the total link attenuation has been calculated using the path integral method. MATLAB software was used to implement and simulate the rain attenuation for HAPS with respect to the stratospheric platform height, earth station height, and the angles of elevation. The obtained results of these calculations will be applied to evaluate the link budget of the HAPS. Thus, in the meantime, the minimum acceptable signal level for the HAPS will be taken as a reference to evaluate the HAPS fade margin of the transmitted and the received signal under rainy channel conditions.

Two mitigation techniques (which are diversity gain and the variable equivalent isotropic radiated power (EIRP)) will be applied to compensate for the loss of the received signal. These techniques were chosen since they are ones of the most efficient techniques in practical. The remote site will be established corresponding to the master site. The signal power which can be gained is a function of the separation distance between the master and the remote sites. The considered clue in this thesis is to let this distance overreach the rain cell diameter during any rain event. As a comparison, the result will be then highlighted to prove the advantage of the site diversity technique.

In additional to the rain attenuation, another issue has been taken into account is the free space loss. Free space loss is one of the main problems facing those systems that operate at high frequencies. The impact of the free space loss will be calculated using the common equation which known as Friis equation which mentioned in Equation 3.12. Subsequently, the result will be added to the rain attenuation to specify the system power threshold.

The results and the outcomes based on these calculations will finally be employed as a reference for the designers to identify the best location of the HAPS system in Malaysia. As mentioned before, Malaysia peninsular needs two stratospheric HAPS segments to cover the entire area. Figure 3.1 shows the methodology flowchart which used as a reference of the thesis progress.

3.2 Coverage Over Peninsular Malaysia

The HAPS technology has many advantages over terrestrial and satellite networks, especially in terms of the coverage area, because it could serve different areas such as islands, oceans, underdeveloped towns, remote and urban areas with highly cost effective service. The satellite cost is quite high as well as for terrestrial systems because of the many access points that are needed to cover these areas. Moreover, 258 ground terrestrial towers are needed to cover the same area thais covered by one HAPS segment. (Al-Samhi & Rajput, 2012)

Based on ITU-R recommendations regarding the HAPS area coverage mentioned in the introduction, two HAPS platforms located at 25 kilometers altitude could cover the whole Malayan peninsular at a minimum elevation angle of 7.5° degrees, since the length of the peninsular is 750 kilometers and the HAPS at height of 25 kilometers can cover a diameter of 380 km at 7.5°, thus two HAPS are needed to cover 750 kilometers. With the lower elevation angle of HAPS, a larger area can be covered. However, the earth stations located at the edges of the coverage are suffering a higher propagation or blocking loss due to the length of the propagation paths and the curvature of the earth. For HAPS Wireless Access, the minimum elevation angle allowed be used is 5° degrees where it is better to use a higher elevation angle in order to avoid or guard against excessive ground clutter problems. Therefore, when the earth stations receives the HAPS signal at an elevation angle of 5° degrees, and the platforms are placed at an altitude of 25 km the area will be covered is approximately 486 km. The ground stations that connect the HAPS network with other terrestrial networks can be placed on the building roofs.

3.3 Location Of HAPS Ground Segments

HAPS platforms altitudes are proposed to be located at 25 km. The Malaysian peninsular has divided into two distinct areas (north and south). The Five earth stations were selected in each part. Each part has it is own environmental characteristics, where these locations have been selected based on the highest rainfall rate amounts. Thus, they are suffering the highest rain attenuation in the peninsular. The stations are listed from north to south respectively. The stations covered by the first HAPS platform are Kampung Sungai Tong, Batu Kurau, Taiping, Kampar, and

Bidor. The second HAPS platform is dedicated to cover the other five locations which are: Tanjung Malim, Kepong, Endau, Jln Kluang Mersing and Kahang Kluang. The coordinates of the 10 stations are listed in Table A.11 (Appendix A)

The elevation angle of these locations can play a very important role regarding the rain attenuation. Therefore, if the total signal path is completely penetrated by rain, the highest elevation angle in this case can produce a smaller attenuation value for the station compared to the result where the elevation angle is lower, and vice versa.

Each location has its own coordinates and rainfall rates. Based on these parameters, each station will receives the HAPS signal at a different angle. Therefore the impact of the rain attenuation will be different at each site. The elevation angles, rainfall rates amounts and the attenuation of these locations are listed in Table 4.2.

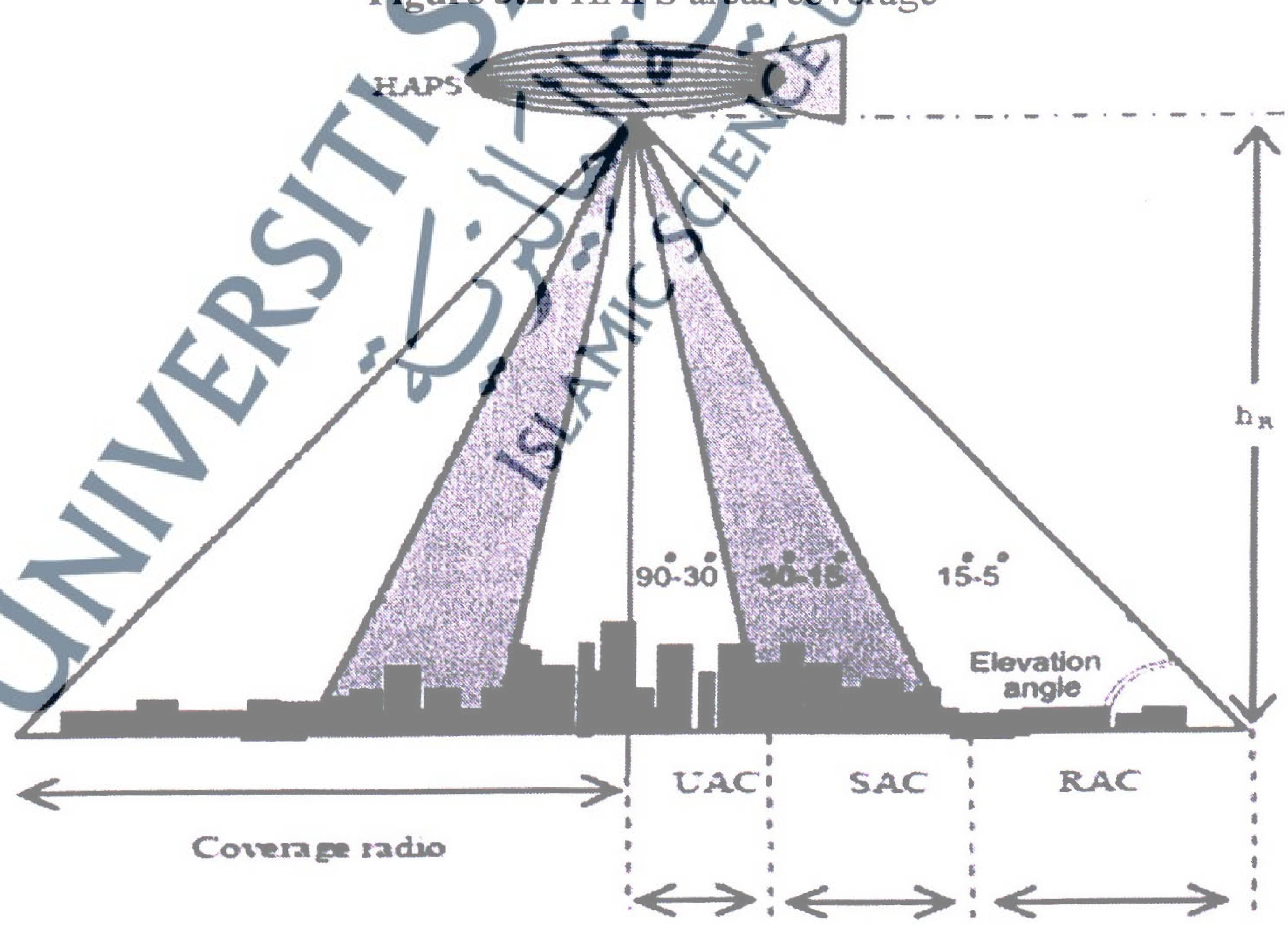
The rain attenuation predicted in this work includes three area coverage, which are (UAC), (SAC) and (RAC). The signal path of each ground station assumed to be impaired by one rain cell. The length of the signal path that will be affected by the rain is dependent on the rain cell size, elevation angle, and the rainfall rate. The rain cell size is dependent on the type of rain as mentioned in Chapter 2, where in the peninsular of Malaysia, the relative cell size is equal 1.25 km (Khamis et al., 2004).

The earth stations that covered by the first HAPS platform (ES1, ES2, ES3, ES4 and ES5) are located far away from each other. The separation distance between ES1 and ES2 equals 231.23 km, 24.22 km between ES2 and ES3, 75.64 km between ES3 and ES4 and 26.57 km between ES4 and ES5. The southern ground stations which are covered by the second HAPS are separated as follows: the distance between ES6 and ES7 equals 51.71 km, 234.22 km between ES7 and ES8, 46.1 km between ES8 and ES9, while the distance between ES9 and ES10 is 15.2 km. All these of stations are receive and transmit the signal with different elevation angles depending on the HAPS platform location.

3.4 HAPS Areas Coverage

HAPS stratospheric segment can deploy multi-beams which capable of projecting numerous spot beams within it's coverage area. The platform acts as the high cell tower. In HAPS system, the platform is located above the ground to create a radio coverage area of up to 500 km. The HAPS system consists of the HAPS platform and number of earth stations located on the ground. Referring to Figure 3.2, HAPS coverage is categorized in three distinct areas: urban area coverage (UAC), suburban area coverage (SAC), and rural area coverage (RAC) that are delineated mainly according to the elevation angles. In other words, the area coverage can be categorized depending on the distance from the sub-platform point (SPP).

Figure 3.2: HAPS areas coverage



Urban Area Coverage is defined as the area that covers 35 km, out from point that located perpendicularly under the platform (ITU-R, 2008). The relative elevation angle extended from 30° to 90°. Suburban Area Coverage extends from UAC to 100 km away from the sub-platform point (SPP), where the relative angle of elevation is from 15° to 30°. Rural Area Coverage is the area extends form SAC to around 243 km. The relative angle of elevation is extend between 15° to 5° degrees.

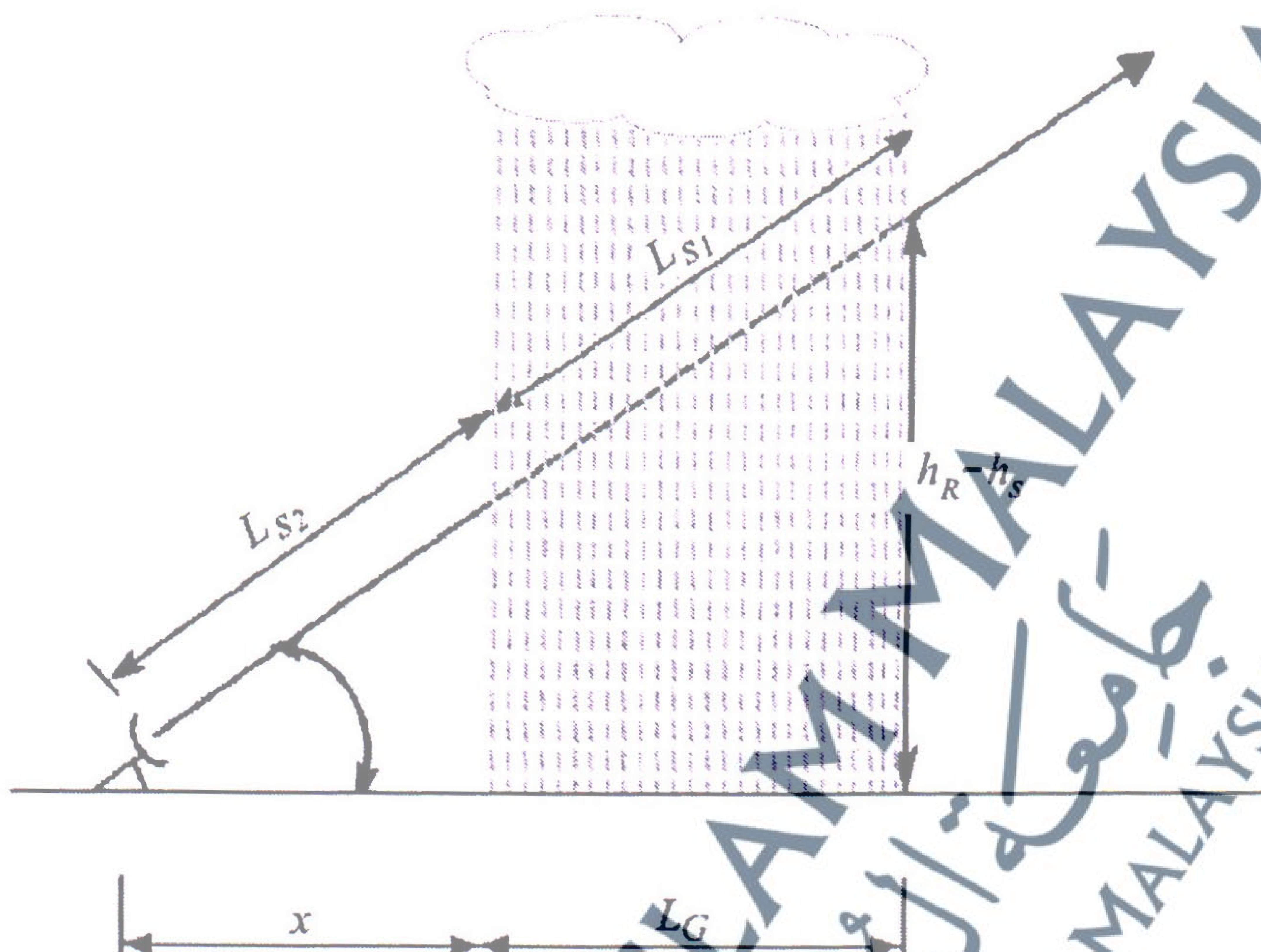
3.5 Modified ITU-R Rain Attenuation Model for Stationary Satellites

The HAPS and Geo-stationary satellites can be regarded as stationary sources (fixed in position) to exchange the data with the receiving station. This is due the fact that HAPS and Geo-stationary satellites have an orbiting period of 24 hours.

There are several models for the rain attenuation prediction related to high frequency bands, where most of them are regional dependence. In this thesis the modified ITU-R model is presented to estimate the actual signal path attenuation in Ka band (28-31GHz). The goal of this model is to provide an accurate method for systems designers to estimate and predict the signal attenuation caused by the rain.

The radio signal impairment through the rain is strongly dependent on the rain cell size, local rainfall rates, rain cloud heights, and signal frequency band. Rain attenuation behavior based on cell size variation is illustrated in Figure 3.3.

Figure 3.3: Prediction scenario for HAPS and stationary satellites



To predict the attenuation using ITU-R Model in case that the signal link is not completely affected by rain as shown in Figure 3.3, it seems that the actual signal path (L_{s1}) affected by rain is shorter than the slant path (L_s) proposed in ITU-R model given by Equations 2.11 and Equation 2.12. Thus, the ITU-R model is not applicable for this case.

The rain attenuation $A_{0.01}$ (dB) for the entire signal path is determined based on the knowledge of the specific attenuation γ_R (dB/km), multiplied with the entire path length of the signal L_E (km). It is given by

$$A_{0.01} = \gamma_R L_E \qquad [dB] \qquad (3.1)$$

where L_E is the effective signal path from the earth station to the height of the rain storm h_R, where it is obtained by

$$L_E = L_{s1} + L_{s2} \qquad [km] \qquad (3.2)$$

The relation between the specific attenuation at a point and the attenuation along the horizon propagation path is determined by multiplying the specific attenuation with the effective path where it is a function of the signal path affected by rain.

The attenuation in the path that is not affected by rain is found as follows.

The path length L_{S2} is given by

$$L_{S2} = \frac{x}{cos\theta} \qquad [km] \qquad (3.3)$$

$$x = \frac{(H_R - H_S)}{tan\theta} - L_G \qquad [km] \qquad (3.4)$$

where x is the horizontal projection of the non-affected path, while L_G is the rain cell diameter.

The effective path length of L_{S2} can be obtained by

$$L'_E = L_{S2}V_{0.01} \qquad [km] \qquad (3.5)$$

The predicted attenuation exceeded for 0.01% of an average year of the signal path L_{S2} is obtained from

$$A'_{0.01} = \gamma_R L'_E \qquad [dB] \qquad (3.6)$$

Finally the overall attenuation can be found by subtracting the attenuation obtained by Equation 3.6 from the total attenuation in Equation 3.1 to get the attenuation for the actual signal penetrated by rain.

$$A_{0.01(LS1)} = A_{0.01} - A'_{0.01} \qquad [\text{dB}] \qquad (3.7)$$

Incorporating all the equations previously (Equation 3.1 to Equation 3.6), the final equation (Equation 3.7) can be written as

$$A_{0.01(LS1)} = kR^{\alpha} L_S V_{0.01} - \left(kR^{\alpha} \left(\frac{\frac{(H_R - H_S)}{tan\theta} - L_G}{cos\theta} \right) V_{0.01} \right) \qquad [\text{dB}] \qquad (3.8)$$

Equation 3.8 is the summary of the new model developed in this thesis, where the first term of the equation $A_{0.01(LS1)}$ is the rain attenuation in dB for the signal part which affected by the rain. The second term is the rain attenuation for the total path, while the third term is the rain attenuation for the path which is not affected by the rain.

The attenuation predicted based on this model is applicable for any annual average time of rainfall rate. The flowchart that representing the modified ITU-R model is shown in Figure 3.4.

The beginning of the first section is to start checking and verifying the system parameters (HAPS altitude, earth station's height, rainfall rate, etc). The initial system parameters are then will be used to predict the attenuation caused by the rain in a distance of 1 km [dB/km], where the calculation of the specific attenuation is depends on the elevation angle, polarization, and the frequency.

The second section is used to calculate the effective path of the signal, where the slant path can be calculated based on the height of the rain, height of the earth station, and the elevation angle. For the case where the elevation angle is $\leq 5^0$, the additional parameter required is the effective radius of the earth. The model defines the effective path (L_E) as a hypothetical path that when penetrated into rain will produce the same path attenuation as the actual rain distribution over the physical path (L_E). The ITU-R model utilizes a vertical adjustment factor and a horizontal reduction factor $v_{0.01}r_{0.01}$ and $r_{0.01}v_{0.01}$ respectively. These factors are obtained empirically (Shkelzen, 2009), where both of them are related to the spatial rain rate variation, frequency, and the signal path length.

The previous steps in section 1 and section 2 are then will be used to predict the attenuation for ITU-R model and the modified model. The rain attenuation for the ITU-R model can be predicted using the specific attenuation, reduction factor, and the slant path length. The prediction of the rain attenuation for the modified model is taking into account the rain cell size, which not accounted in the ITU-R model. Thus, the modified model is able to predict the rain attenuation when the signal is partially or completely affected by the rain.

Figure 3.4: Flow chart for the Modified ITU-R Model

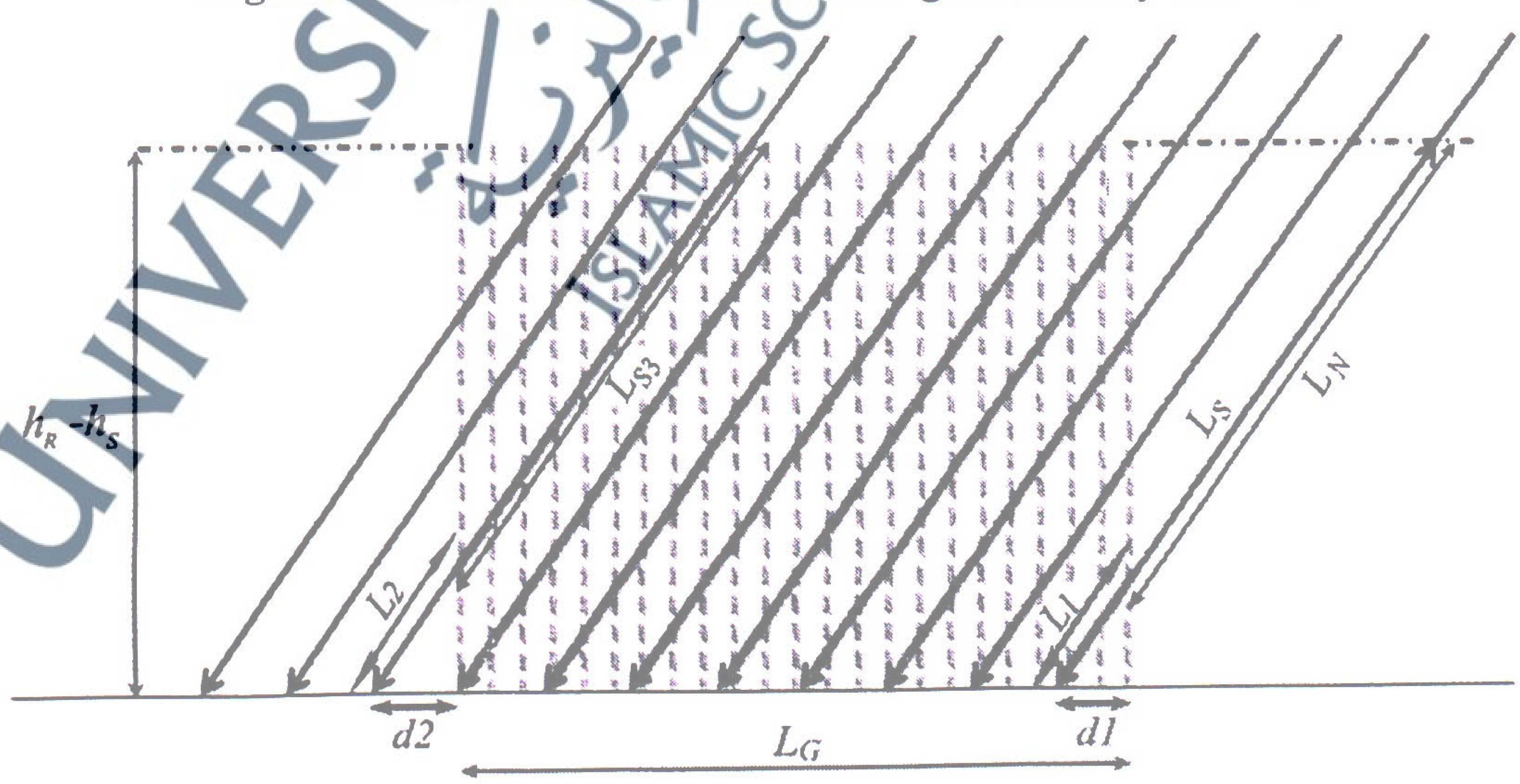
3.6 New Rain Attenuation Model for Non-stationary Satellites

Rain attenuation is a common, yet often very complicated weather event that degrades the wireless communication signals in the presence of rain. It cause fading for all types of satellite signals e.g. Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO).

In this section, a new model has been developed to predict the rain attenuation for the non-stationary satellites such as, MEO and LEO. These types of satellites are moving faster than the earth, thus they are not regarded as stationary sources to the receiving station. The proposed rain prediction model for stationary satellites is presented in Section 3.5.

This model uses the reduction factors of the ITU-R rain attenuation model described in Section 2.17.2. Attenuation prediction using this model requires the knowledge of some parameters such as rainfall rate statistics data, the velocity of both the satellite and the clouds, and the rain cell size. Figure 3.5 shows the non-geostationary signal scenario penetrated in the rain.

Figure 3.5: Prediction scenario for non-geostationary satellites



The attenuation of the satellite signals can be predicted as follows:

The rain attenuation $A_{0.01}$ (dB) for entire signal path at any percentage of time can be determined from

$$A_{0.01} = \gamma_R L_E \tag{3.9}$$

where γ_R is the rain specific attenuation in (dB/km), L_E is the effective path length of the signal which penetrated in the rain.

Before predicting the signal, it is necessary to know the satellite speed in order to calculate the distance of the signal penetration in the rain at certain time, where in this task the satellite speed at the ground is assumed to be 6.9 km/s. [Vanicek & Christou, 1993]

$$d = vt \tag{3.10}$$

Since v=6.9 km/s, therefore at t=0.001 second the signal penetration distance in the rain is equal 0.0069 km.

Once the signal path goes though the rain cell, the effected path will gradually increases, where the maximum length for the penetrated path will equal to $\frac{L_G}{cos\theta}$.

The path length at the first 0.001second is calculated by

$$L_1 = \begin{cases} \frac{d_1}{cos\theta} & L_1 \le L_S \\ \frac{h_R - h_S}{\sin\theta} & otherwise \end{cases} \tag{3.11}$$

where d_1 can be calculated by subtraction the clouds velocity from the satellite velocity if the cloud moves at the same direction with the satellite, while it is equal the summation of clouds and satellite velocities when the satellite and the clouds moving in opposite directions.

In case of same directions, $$d_1 = d_s - d_c \quad (3.12)$$

If opposite directions, $$d_1 = d_s + d_c \quad (3.13)$$

The slant path L_S assumed to be totally penetrated in the rain, where it can be calculated either from Equation 2.11 or Equation 2.12.

The reason of proposing the slant path is totally penetrated in the rain is to imagine that the non-affected path is the one that affected while neglecting the path that truly penetrated in the rain. The non-affected path L_N is equals

$$L_N = L_S - L_1 \quad (3.14)$$

Since it is known that the rain spatial is not uniform, the vertical reduction factor is used to calculate the non-uniformity of the rain. Therefore the effective L_N is calculated as follows

$$L_{EN} = L_N v_{0.01} \quad (3.15)$$

The predicted attenuation exceeded for 0.01% of an average year for the signal path L_{EN} can be obtained by

$$A'_{\ 0.01} = L_{EN}\gamma_R \quad (3.16)$$

so far, the rain attenuation of the imaginary path has been predicted, thus the overall attenuation is founded by subtracting the attenuation in Equation 3.16 from the total attenuation in Equation 3.9 to get the attenuation for the actual signal penetrated by rain.

$$A1_{0.01} = A_{0.01} - A'_{\ 0.01} \tag{3.17}$$

The second step is to calculate the path length L_2 when the signal path exceeds the rain cell by a distance of d_2. It can be seen that the signal path penetrated in the rain will decrease gradually as the satellite moves. Therefore L_2 has been calculated as follows

$$L_2 = \begin{cases} \dfrac{d_2}{\cos\theta} & L_2 \leq L_S \\ \dfrac{h_R - h_S}{\sin\theta} & otherwise \end{cases} \tag{3.18}$$

The path length will decreased by the amount of L_2 of each the satellite moves, therefore the path length which affected by rain can be obtained by

$$L_{s3} = L_{s2} - L_2 \tag{3.19}$$

where,

$$L_{s2} = \begin{cases} \dfrac{L_G}{\cos\theta} & L_{S2} \leq L_S \\ \dfrac{h_R - h_S}{\sin\theta} & otherwise \end{cases} \tag{3.20}$$

The effective path length L_{s3} of the signal is found by multiplying the actual path penetrated in the rain by the vertical reduction factor $v_{0.01}$

$$L_{Es3} = L_{s3} v_{0.01} \tag{3.21}$$

The rain attenuation of the signal path affected by rain can be calculated by

$$A2_{0.01} = L_{Es3} \gamma_R \tag{3.22}$$

This model is valid to predict the rain attenuation for LEO and MEO satellites at any time percentage of average a year.

3.7 Rain Attenuation Prediction Using Convolution Method

Mathematically, a convolution is defined as the integral over all space of one function at *x'* times another function at *x-x'*. The integration is taken over the variable *x'*, from 0 to the rain cell size, which in this study equals to 1.25 km. The convolution is, therefore, a function of a new variable *x*, as shown in Equation 3.23 and Equation 3.24, where the cross in the circle is used to indicate the convolution operation.

$$f(x) = g(x') \otimes h(x') \tag{3.23}$$

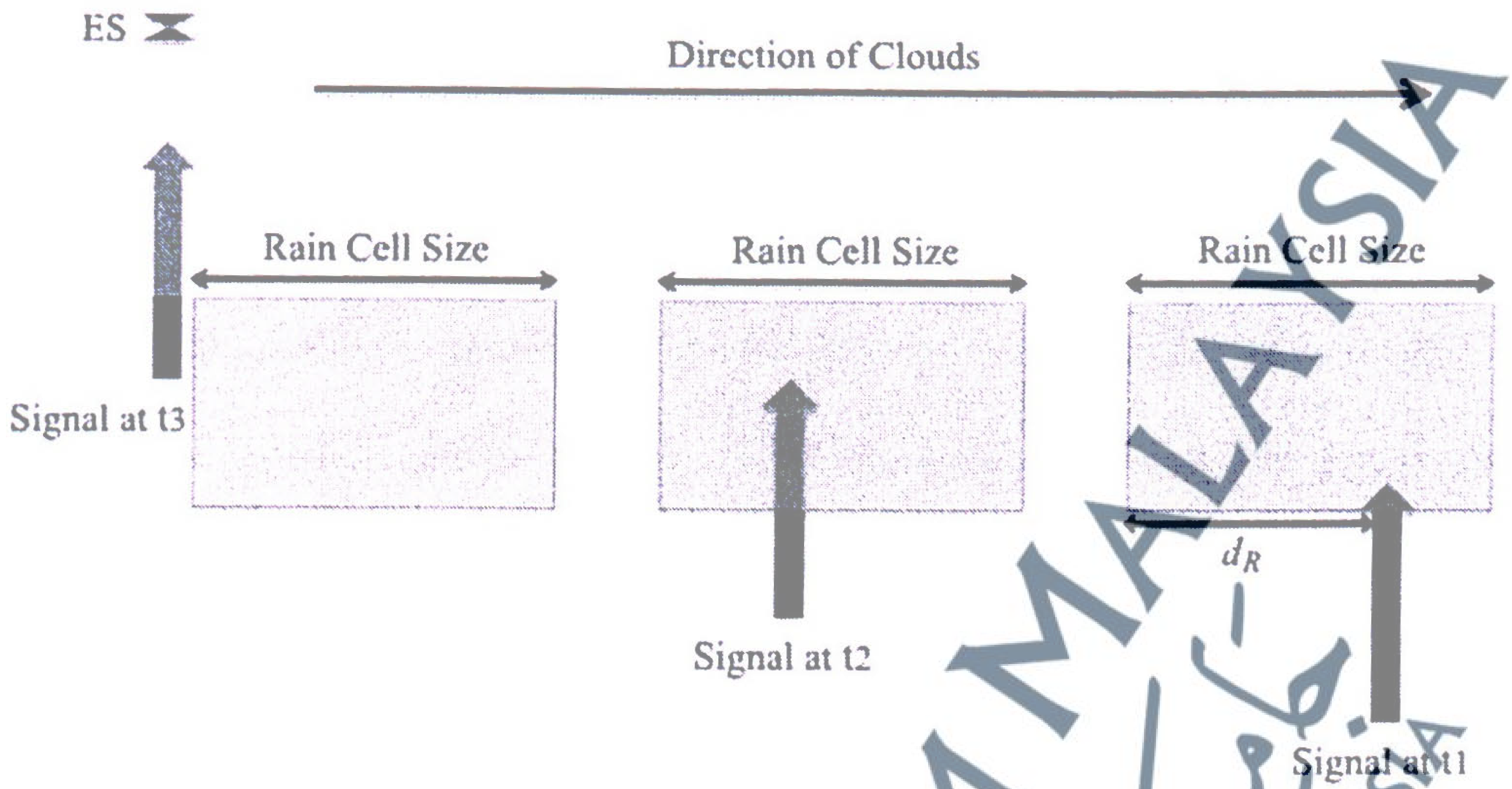
$$f(x) = \int_{-\infty}^{\infty} g(x')h(x - x')dx' \tag{3.24}$$

where: $g(x')$ is the specific attenuation in [dB/km], which is a function of the average time that the rain is exceeded in a year, and the operation frequency in GHz. $h(x')$ is the effective slant path penetrated into the rain in km.

3.8 Effective Rain Cell Size

In general, clouds move at a speed and direction of the prevailing wind at the altitude where the clouds are forming. The direction and speed of the wind depends on the pressure differences between the areas of high and low pressure. As the altitude increased over a particular location, the winds will vary in direction and speed. Usually, the wind speed increases with altitude up to a certain point, and then the speed will be unstable. Rivers of fast-moving air in the atmosphere are called "jet streams", they occur at an altitude from 26 to 40 km above the ground. Speeds in the jet stream can reach as high as 450 kilometers per hour or more. When clouds occur at that level, the clouds move very fast. The location and strength of the jet stream has a big effect on the weather at a particular location. At a lower level, the wind speed and the direction are varying from location to another. Figure 3.6 illustrates the scenario of the signal penetration into the rain for LEO and MEO satellites.

Figure 3.6: Time series of non-geostationary satellite signal penetrated in rain



It can be seen that the effective size of the rain cell is not equal to the rain cell size due to the movement of both the clouds and the satellite. However, the effective cell size depends on the initial position of where the signal touched the cloud at the first moment of the penetration.

Based on a deep study that has been done in this work for estimating the behavior of the satellite versus the clouds movement, the effective cell size of the rain cell can be obtained by

$$RC = S_S + \left(\frac{S_S}{C_S} * d_R\right) \qquad \text{[km]} \qquad (3.25)$$

$$Effective\ rain\ cell\ size = \begin{cases} RC - (RCSE - RCS), & RC \geq RCS \\ RC & , Otherwise \end{cases} \qquad \text{[km]} \qquad (3.26)$$

where

RC is the rain size in [km].

S_S is the satellite speed.

C_S is the cloud speed.

d_R is the distance between the initial position of where the signal touched the cloud at the first moment of the penetration, and the edge of the rain cell.

The effective rain cell size calculation method is utilize four parameters (v_s, v_c, RCS, and d_R) that can be adjusted depending on the velocity of both the satellite and clouds, the touching point distance of the signal to the rain cell and the rain cell size.

3.9 Fade Mitigation Techniques

Wireless links can be impaired by the random fluctuations in the signal level across the space. This phenomena is called attenuation. Signal degradation due to rain is one of the obstacles facing the HAPS Communication technology especially in a tropical region like Malaysia, because the rain in this region has a higher rainfall intensity than those located in other regions. Due to the variable channel conditions, mitigation techniques must be applied to guarantee the wanted service availability of the systems. Many techniques have been developed to compensate for the signal attenuation caused by the rain. In this study, site diversity and EIRP techniques will be considered.

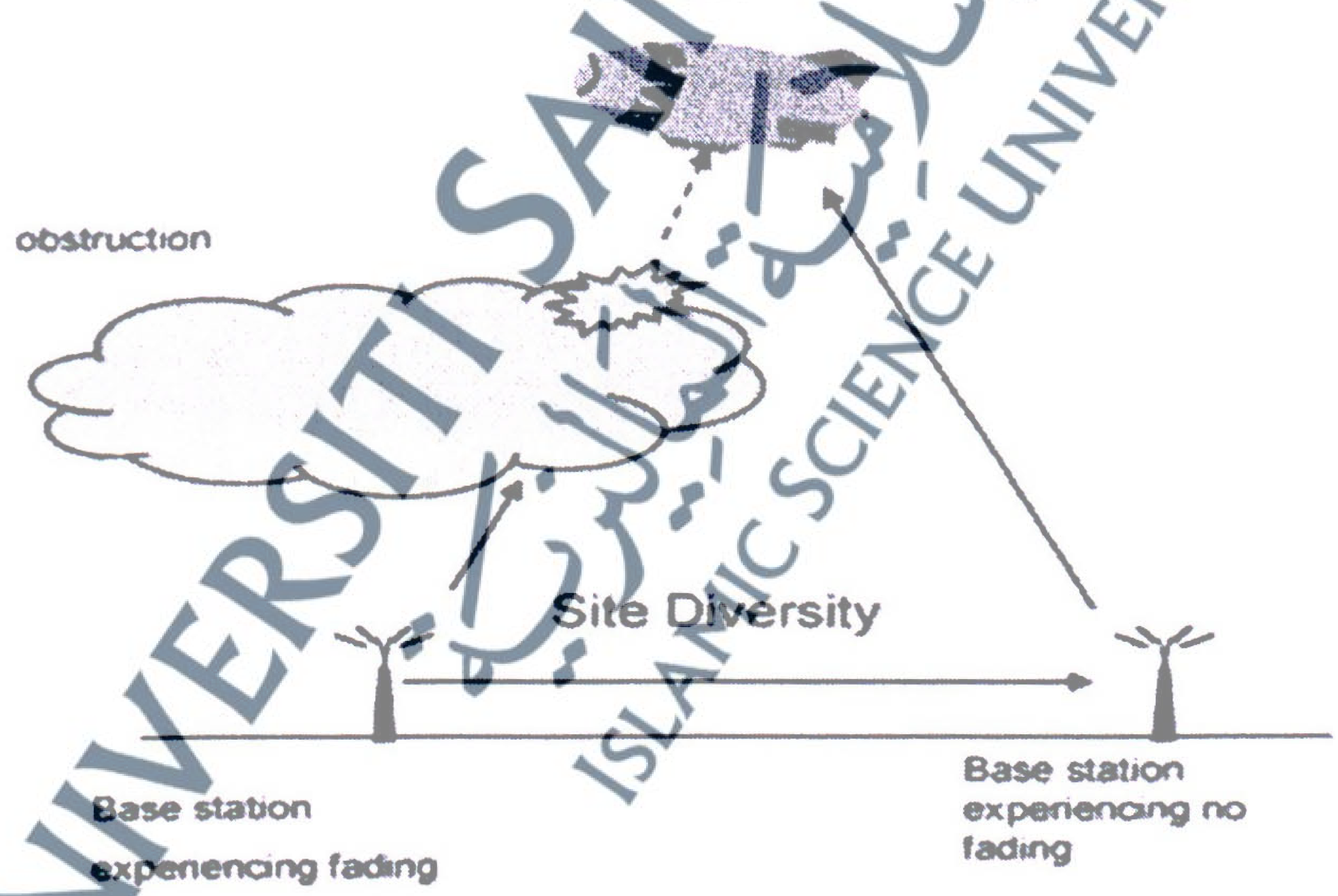
3.9.1 Site Diversity Gain

Site diversity is one of the most effective solutions to improve the link availability by relaying the signal from the diverse site to the main site. Site diversity technique utilizes master and remote stations located several kilometers apart to take the advantage of the non-homogeneity of the rainfall intensity (Enjamio et al., 2002), as shown in Figure 3.7. This technique can be used when the probability of the outage might occur on the main site due to heavy rain. Since the diverse site is a few kilometers away from the rain cell, it will unlikely suffer the same attenuation. Therefore, the availability of the system will increase. The site diversity technique simply depends on single site attenuation and one or more joint sites attenuation, where the joint site attenuation must has the minimum rain attenuation compared to the other site. For instance, if A_1 is the attenuation of the site 1 and A_2 is the joint site, the attenuation A_j is given by:

$$A_j = \min\{A1, A2\} \tag{3.27}$$

The signal received by the joint site is rerouted to the master station where it is further processed based on either signal selection switching or using signal combiner units.

Figure 3.7: Site diversity scenario



The simplified prediction method used in this thesis is the site diversity gain G_{SD}, which is defined as the difference between the single site attenuation A_S, and the joint site attenuation A_D, expressed in decibel [dB], for the same rainfall percentage in average year (Timothy Pratt et al., 2001).

$$Gs_D\ (\mathrm{p}) = A_S\ (p) - \ A_D\ (p) \tag{3.28}$$

In the meantime, an accurate expression can be used to calculate the power which can be gained by applying the site diversity technique, which can be written in a simple form. The calculation of the site diversity gain follows these steps.

The gain contributed by the spatial separation can be calculated as

$$G_d = a\ (1 - e^{-bd}) \tag{3.29}$$

where:

$$a = 0.78A - 1.94\ (1 - e^{-0.11A}) \tag{3.30}$$

$$b = 0.59(1 - e^{-0.1A}) \tag{3.31}$$

Calculation of the frequency-dependent gain can be obtained by

$$G_{f=} e^{-0.025f} \tag{3.32}$$

Calculate the gain term dependent on elevation angle from

$$G_\theta\ = 1 + 0.006\ \theta \tag{3.33}$$

Calculate the baseline-dependent term from the expression

$$G_{\phi} = 1 + 0.002\ \Psi \tag{3.34}$$

The net diversity gain as presented in Equation 3.35

$$Gs_D = G_d \,.\, G_f \,.\, G\,\theta \,.\, G\,\phi \tag{3.35}$$

where:

d is the separation (km) between the two sites

$A_{0.01}$ is the path rain attenuation (dB) for a single site

f is the frequency (GHz)

θ is the path elevation angle (degrees)

Ψ is the angle (degrees) made by the azimuth of the propagation path with respect to the baseline between sites, where in this work is assumed to equals 90°.

3.9.2 Variable Equivalent isotropic radiated power

The equivalent isotropic radiated power is one of the techniques used to mitigate the rain attenuation. The margin value of the HAPS link is needed in order to apply this technique. In this task, it is assumed that the EIRP of the HAPS will increase corresponding to each rain attenuation event that affects the transmitted and the received signal for each location. Some parameters were initially assumed to facilitate the calculations as shown Table 3.1:

Table 3.1: HAPS system parameters

Parameter	Value
Downlink frequency	28 GHz -31 GHz
EIRP	105 dB
Free space loss	Variable
Rain attenuation	Variable
Transmitted antenna power	50 dB
Transmitted antenna gain	55 dB
Link margin	Variable

The received power can be obtained as below:

$$P_r = EIRP + G_r - L_{fs} - A_{0.01} \quad (3.36)$$

where:

$EIRP$ is Equivalent isotropic radiated power (dB).

G_r is Receive antenna gain (dB)

L_{fs} Free space loss

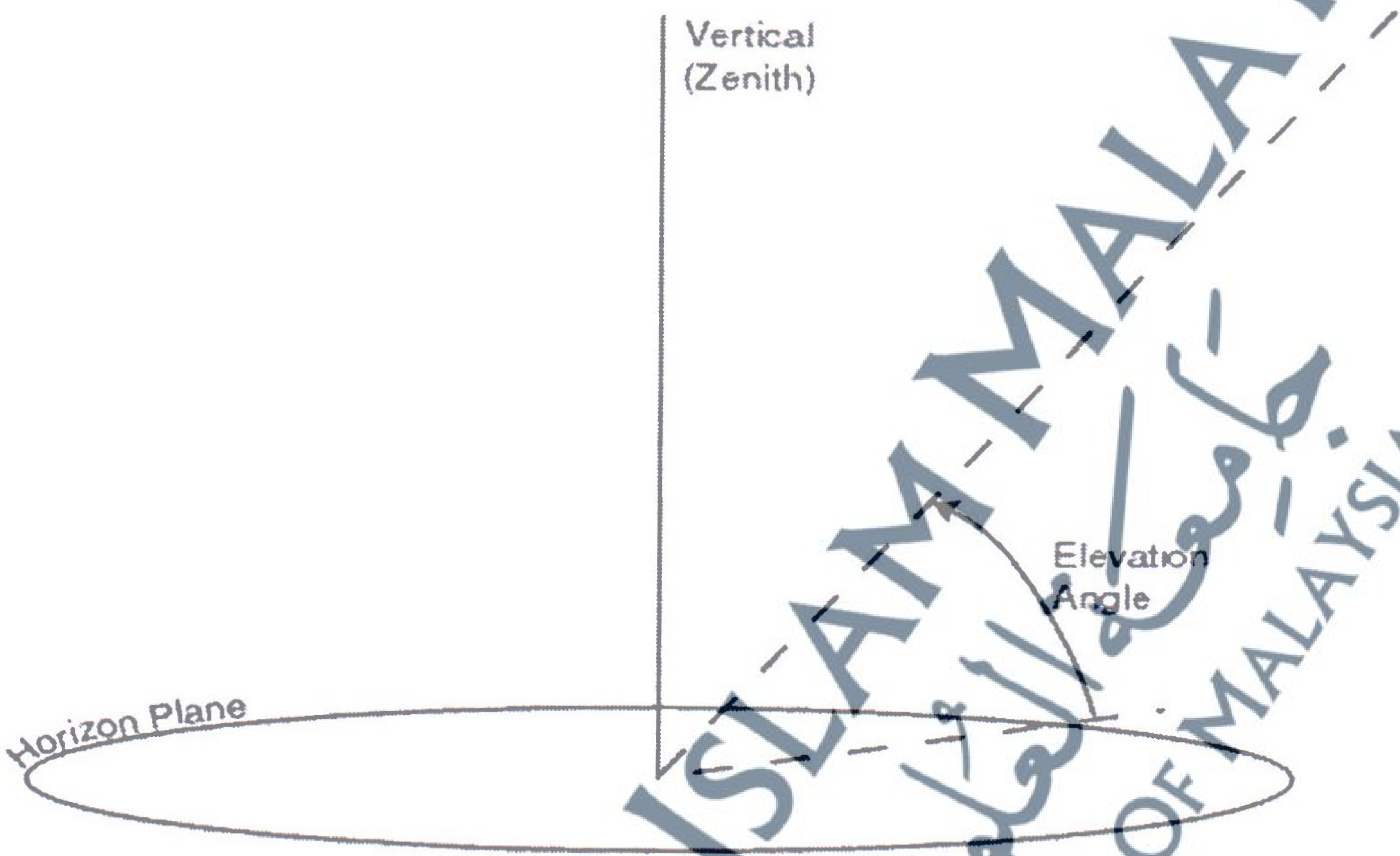
$A_{0.01}$ Rain attenuation predicted at a particular location

3.10 Dependence of Elevation Angle

When the signal link is completely affected by rain, the attenuation due to rain can be reduced by increasing the operational elevation angle of the HAPS ground segment (Schwarzenbarth et al., 2007). Moreover, not only can the elevation angle play an important role for the rain attenuation, but it is also does in the clear sky event, where the free space path loss reaches the minimum value at a high elevation angle.

Elevation angle refers to the angle between the beam direction towards the HAPS, and the horizontal plane, as shown in Figure 3.8.

Figure 3.8: Antenna elevation angle



When the total path is being affected by the rain, and the minimum operational angle of the HAPS ground station is increased from 30° to 70° degrees, the rain attenuation is reduced to about 90 dB. However, in case of the path partially affected by the rain, the rain attenuation increases about 40 dB when the elevation angle varies from 30° to 70° degrees.

3.11 HAPS Link budget

Typically, the communication path between HAPS and the terrestrial terminals is a line-of-sight connection. This type of link is highly affected by the free space propagation loss, because the operational frequency band of the HAPS is above 10 GHz. In this section, the basic wireless communication theory will be applied to calculate the HAPS link budget.

The link budget is a process to estimate and assess the gains and losses of the transmitter and the receiver over the channel media for any telecommunication system network. To calculate the budget of such a link, several factors must be taken into consideration, because they are playing an important role for the signal strength such as the channel distance, transmitter and receiver antenna gains, and transmitter and receiver power (Cheblil, 1997). For the random varying channel conditions, some margin can be added depending on the expected severity for the attenuation impact. A simple link budget equation is described as follows.

$$P_r = EIRP + G_r - L_{fs} - A_{0.01} \tag{3.37}$$

where:

P_r is the received signal strength.

$EIRP$ is the equivalent isotropic radiated power (dB).

G_r is the received antenna gain (dB).

L_{fs} is the free space loss.

$A_{0.01}$ is the rain attenuation predicted at a particular location.

Some parameters are assumed to calculate the HAPS Link budget by using the link budget formula which presented in Equation 3.37, where the parameters are listed in Table 3.1.

3.11.1 Free-Space Propagation and Path Loss Theory

The Friis equation is used to estimate the signal loss due to the free space or an atmospheric medium. Thus, this equation is valid whether the medium is a rainy or in clear sky events.

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{3.38}$$

where:

P_r is the power received

P_t is the power transmitted

G_t is the transmitter antenna gain

G_r is the receiver antenna gain

L_{fs} is the free space loss

d is the distance between transmitter and receiver,

λ is the wavelength of radio wave.

To simplify the pervious equation (Equation 3.38), it can be represented it to be in decibel (dB). The formula to represent the received power in dB is given as

$$P_r = \frac{P_t G_t G_r}{L_{fs}} \tag{3.39}$$

The free space loss between the HAPS and the ground station L_{fs} is given by

$$L_{fs} = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{3.40}$$

When representing the Friis equation in decibels (dB), we have

$$L_{fs} = 10log\left(\left(\frac{4\pi df}{c}\right)^2\right) \tag{3.41}$$

$$= 20log\left(\frac{4\pi df}{c}\right) \tag{3.42}$$

The parameters are substituted as follows

$$= 20log_{10}(d) + 20log_{10}(f) + 20log_{10}\left(\frac{4\pi}{c}\right) \tag{3.43}$$

The loss of the signal caused by the free space can be found by

$$L_{fs} = (dB) = 20log_{10}(d) + 20log_{10}(f) + 92.45 \tag{3.44}$$

where the frequency (*f*) is in GHz and the distance (*d*) in km

In this thesis, the frequency used for HAPS is 28 and 31 GHz while the altitude of the HAPS platform height is 25 km. Thus, the calculated free space loss at the sub-platform point (SPP) for the downlink is found below:

$$L_{fs_{(28)}} = 92.45 + 20\log 25 + 20\log 28 = 149.35\text{ dB} \tag{3.45}$$

In case of the uplink, the free space loss can be calculated as follows

$$L_{fs_{(31)}} = 92.45 + 20\log 25 + 20\log 31 = 150.24\ \text{dB} \quad (3.46)$$

However, the amount of the free space loss is located in different locations, the amount of the free space loss for the uplink and the downlink will be different because they are transmitting and receiving the HAPS signal in different elevation angles.

3.11.2 Fade Margin

Fade margin is defined as the difference between the received signal power at the receiver input and the minimum acceptable signal power level in dB. The amount of the fade margin required is depends on the link immunity to the attenuation at which the link is designed, where the higher the fade margin, the more link reliability. Practically, the receiver must has a fade margin above zero dB, to ensure that the received signal is higher than the threshold.

$$Fade\ margin\ (dB) = received\ signal\ (dB) - receiver\ threshold\ (dB) \quad (3.47)$$

In this thesis, the fade margin is calculated by referring to three different receiver thresholds that were set as -45 dB, -75 dB and -100 dB.

3.12 Software Tools

To predict the rain attenuation of the ITU-R model or other models, software programming is the best way to go through such a process. Software programs have many advantages, not only to reduce the burden of the calculation process conventionally, but the results can also be presented in more convenient way. The software tool can helps the user to obtain the required results by just setting up the values of the input parameters and waiting for the results. There are many options for the user for developing their source code such as, C++, BASIC, PASCAL, MATLAB or any other high level languages. MATLAB software has been chosen because it is ranked as one of the best programming tools, with many built-in functions that can reduce the burden of the overall work, and obtaining accurate results.

The calculation of rain attenuation based on these models has long procedure steps. Therefore, in order to guarantee accurate prediction results, software tools are very important to be used. Thus, the full MATLAB code is illustrated in Appendix B through Appendix K.

3.13 Summary

The understanding and the modeling of channel impairments are important to design any communication system. The purpose of this chapter is to describe the research methodology of this study, describe the characteristics as well as the location of the ground stations. The proposed models that able to predict the rain attenuation for HAPS and satellite are also discussed. The models reviewed in this chapter to predict the rain attenuation represent different methods estimate the slant path rain attenuation. Although each model dedicated for different scenario, some characteristics are identified. All the models assume that the rain microstructure is constant for all geographic regions and the specific attenuation can be approximated by the power law relationship.

The chapter also provides an explanation of the procedures used to design the link budget. The design of HAPS system begins with a set of parameters that affects the overall system performance such as HAPS altitude, elevation angle, and the coordinated of the ground stations. Amongst the various procedures employed to support the design and development of HAPS communication systems, the link budget stands out in its ability to provide overall system insight. By examining the link budget, the factors regarding the overall system design and performance can be identified. This chapter discusses the mitigation techniques that used to enhance the signal strength and to guarantee the wanted service availability of the systems.