

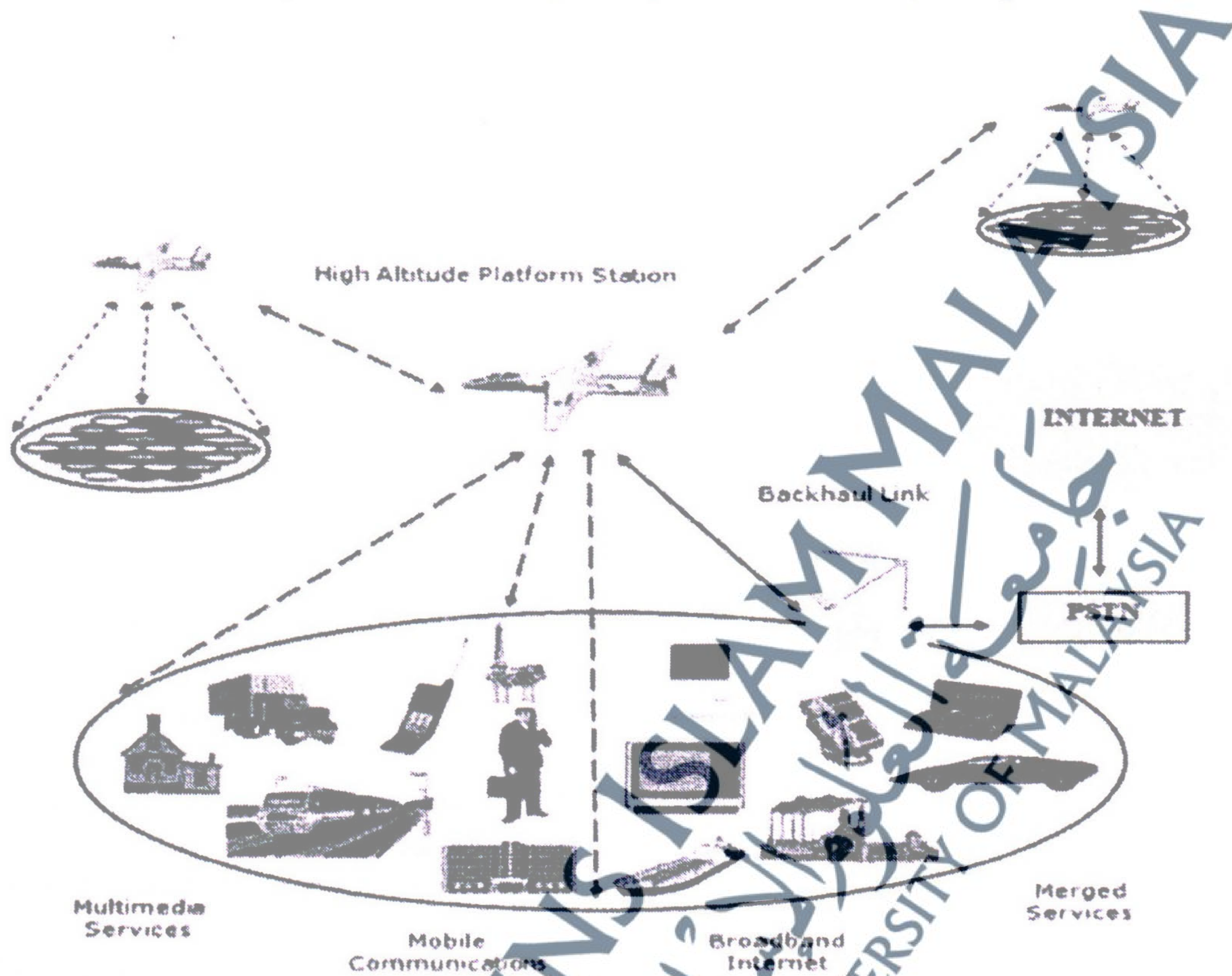
## CHAPTER II: LITERATURE REVIEW

### 2.1 Introduction

High-altitude platform stations is a promising technology that combines the advantages of both terrestrial and satellite communication systems to deliver multi-services broad or wideband communications to the users at a low cost. HAPS can deploy very fast, is easy to maintain and is able to cover very wide areas. HAPS technology offers a good alternative for network operators who are looking for a way to keep up the market demands. HAPS can provide more coverage to deliver a wide range of multi-media services to fixed and mobile terminals as shown in Figure 2.1. With the continuing growing of the wireless communications market as well as to achieve the customer demands, the federal government of Malaysia has conducted many research studies about HAPS, where it is finally cooperated with the Russian and Irish QucomHaps Company to design an M-55 stratospheric aircraft (Wanis & Ahmad 2013). That agreement will enable the M-55 aircraft to fly above the Malaysian skies to provide advanced wireless services such as wide and broadband to users at a low cost (Geoscan et al., 2004; Alejandro et al., 2008). The global vision expects that the HAPS network will consist of one or more stratospheric segments, depending on the area. Each segment is associated with a number of gateway stations on the ground to provide the interconnection with the telecommunication networks for rural or remote areas.



Figure 2.1: HAPS System [Wanis & Ahmad, 2013]



## 2.2 Rain Attenuation Studies

The atmosphere consists of 3 different layers. When the high frequency waves propagate in the atmosphere, the signal power will decay due to the natural phenomena such as rain, fog, gases, clouds, water vapor, or the scintillation. Rain attenuation dominates the other forms of precipitation. It is a combination of the absorption and the scattering that affects the signal.

The impact of rain attenuation on the high frequency signals varies as a function of different parameters such as the rainfall rate, frequency, polarity, and the elevation angle (Accuille, 1998) The rain attenuation occurs due to scattering when the wave



passes through the airborne raindrops. The absorption is dominant for radio frequencies above 10 GHz. Within Ka-band, it is noticed that the signals suffering rain attenuation about three times higher than those caused when using C-band. Many research studies have been done for different frequencies all over the world, especially in Malaysia, Japan, Nigeria and Italy, to predict the attenuation in an accurate manner. Several models and methods have been proposed to overcome this issue.

Lin in 1979, proposed a model to predict the earth-space rain attenuation links. The advantage of this model is the simplicity, although it has some disadvantages such as the lack of the frequency dependence. This model had been tested against real data only for the United States. As a result, the model's performance is unknown in other locations such as tropical areas.

Crane in 1977, proposed a model for the rain attenuation prediction of both the terrestrial and earth-space links. The model is based on the geophysical observation of the rainfall rate, rain structure and the vertical variation of atmospheric temperature. The prediction mechanism of this model calculates the attenuation at a point then the path integral method is used to obtain the total attenuation of the path.

The CCIR empirical model has been proposed to estimate the long-term slant-path attenuation. The CCIR model is given in two forms. The first version is based on the rainfall rate at 0.01% of the average time. This form is only recommended in a maritime climate. The second version is slightly different where it is recommended worldwide. Maritime and the continental climates are described in the CCIR 1981a report.

A semi-empirical model for the rain attenuation prediction of slant-path was developed by VPI and SU. It was originally used as part of a sophisticated scattering model to calculate attenuation and depolarization, and was then refined by Wiley,



Stutzman and Bostian in 1974 to provide a simple means of estimating slant-path attenuation. Extensive comparisons was done for this model to many sets of real data performed by Stutzman and Bostain with good results.

One of the best mitigation techniques is called Effective Isotropic Radiated Power (EIRP) where the magnitude of gain and the transmitted signal power can be adjusted as the HAPS link budget varies. At the clear sky condition, the EIRP will automatically be adjusted to the normal value to achieve the desired signal quality.

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. The master site depends on one or more remote sites located several kilometers away from the station of interest to improve the link availability by relaying the signal from the remote site to the master site. Site diversity is a useful technique when the probability of an outage might occur at the main site due to heavy rain. The availability of the system will increase since the diverse site is located few kilometers away from the rain cell and it is unlikely to suffer the same attenuation. The site diversity technique simply depends on single site attenuation and one or more joint sites attenuation. The received signals will be sent to the master station for processing based on either signal selection switching or combining before they are sent to the master site. The diversity control unit coordinates the signals flow between the master and remote sites (Cheblil, 1997)

Adaptive coding scheme was proposed to improve the signal quality when the attenuation event takes place. The channel coding adds a redundancy bits to the message to detect and correct the errors produced due to the degradation sources.

Adaptive coding is a technique that employs a variable coding rate, where the resulting code word adaptively changes depending on the fade conditions. There are various possibilities to implement variable rate codes such as orthogonal codes, to



allow the decoder to recover the original message within low errors (Fukuchi & Saito, 2007).

Additionally, many other models dedicated for rain attenuation prediction have been proposed by different researchers. The concept of most of those models is either utilizing the path integral or they are based on the power law approximation.

### 2.3 Rain Attenuation Modeling

The studies of rain attenuation behavior began after World War II and have continued until today (Hao et al., 2000). Most of the rain attenuation studies assumed that the signal power decays exponentially when penetrated in rainy medium. Some of the prediction studies are based on the microstructure of the rain, while others conclude that the rain attenuation can be obtained using the power law approximation.

The aim of the attenuation modeling is to provide a suitable method for communication system designers to predict the amount of the attenuation for the communication links. Many models are in used in different regions in the world to estimate the impact of rain on the signal links. The prediction efficiency varies among those models based on the signal link characteristics and the geographical characteristics of the location of interest. The variation is due to the deficiency of the calibration methods used, where some models are able to predict the attenuation efficiently in certain regions but they were found to be not that efficient when they were tested in areas have different climatic characteristics.

The International Telecommunication Union for Radio (ITU-R, 2010) has recommended the average time of the rainfall rate is 0.01% of the year to guarantee the system service availability of a microwave link to be 99.99% throughout the year.



Specific attenuation and effective path length are the main parameters for the ITU-R model. These parameters will be discussed in the next sub-sections.

## 2.4 Types of Rain

The precipitation characteristics are vary based on the climate region and this variation is appreciable between the tropics and the non-tropical regions. The precipitation can be classified into two types: convective and stratiform rain (Das et al.; Ajayi & Barbaliscia, 1990).

Stratiform precipitation is produced from the formation of small ice particles joined together to create a large nucleus. When the nucleus passes through the melting layer, (extending from about 0.5 to 1 km below the  $0^{\circ}\text{C}$  isotherm) it will be converted into a raindrop that falls to the earth's surface, with a horizontal extent of tens of kilometers for durations exceeding an hour. The vertical extent is up to the height of the bright band. Convective precipitation is associated with clouds that are formed in general, below the  $0^{\circ}$  isotherm and are stirred up by the strong movement of air masses caused by differences in tropospheric pressure. In this process, water drops are created and grow in size, until they fall to the earth's surface. The horizontal scale of the clouds are widespread diameters extending up to several kilometers for durations of tens of minutes (Ajayi, 1989; Capsoni, 2009). Tropical rainfall is often convective and characterized by high rainfall rates. As the opposite of the stratiform rain, the convective precipitation occurs, in general, over a small vertical extent, only for several kilometers and for a short duration of time (Ajayi, 1993). However, during precipitation, convective rain is generally heavy due to large drop size and high rain intensity. Convective rain tends to have lighting, thunder, and heavy rain while the



stratiform rain is more of a gentle long lasting rain with no lightning and thunder.

## 2.5 ITU-R Global Rainfall Rate

The International Telecommunication Union for Radio (ITU-R) has divided the world into 14 climatic zones where the rainfall varies from 8 to 145 mm/hr. The ITU-R map has categorized Malaysia as Region P, which is one of the very high rain precipitation regions. The global map of 0.01% of an average year is shown in Figure 2.2.

**Figure 2.2:** Rainfall global climatic zones [www.ec.gc.ca, 2013].



## 2.6 Relation between rain and attenuation

The attenuation of radio signals due to the rain is the main reason for degradation of communication systems above 10 GHz (Williams, 2002). The frequency bands assigned by the ITU-R for HAPS technology (28-31 GHz in Asia and 48-51 GHz worldwide) are selected based on the amount of rain attenuation of those regions,



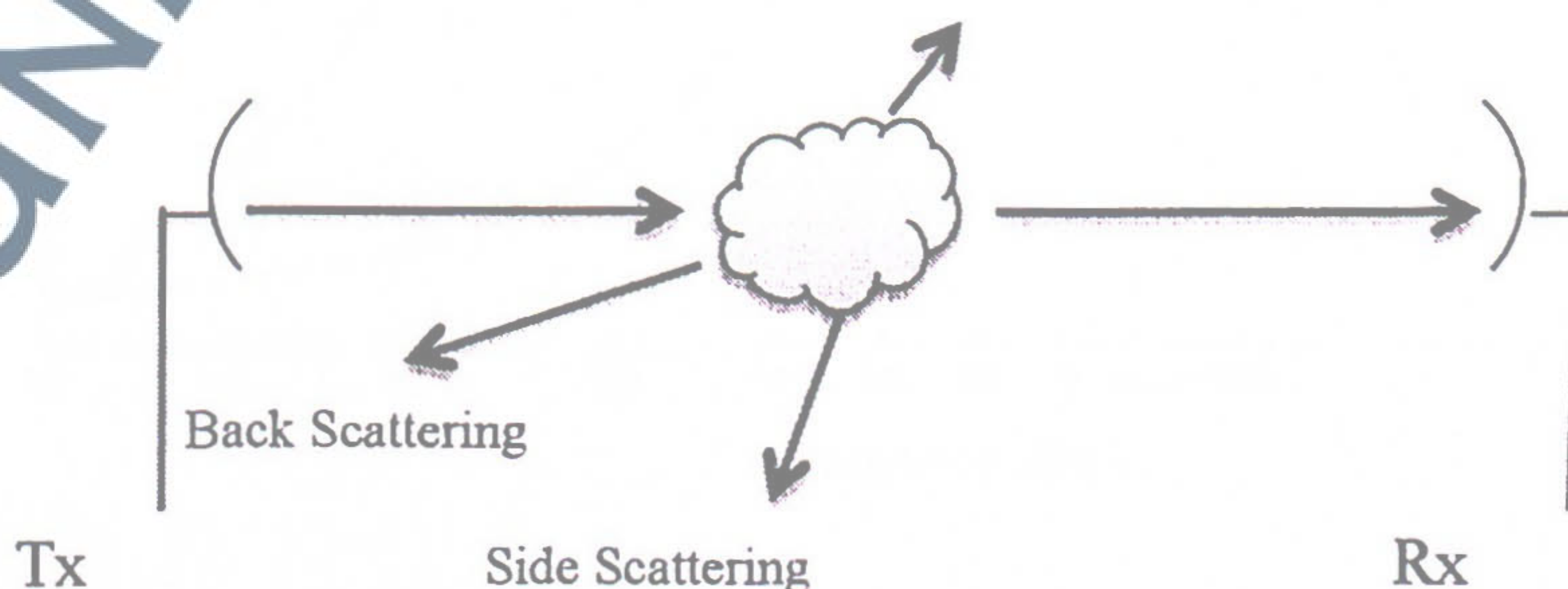
which is the dominant cause of HAPS and terrestrial signal degradation in tropical zones (Ajayi, 1990).

The attenuation due to raindrops is greater than the attenuation due to other forms of precipitation. Rain attenuation is caused by the absorption and scattering of the signal, in which the raindrop acts as poor dielectric material. The drop of rain decays the power of radio waves and dissipates it by scattering and absorption. Raindrops cause greater attenuation by scattering than absorption at frequencies above 100 MHz (Zhenwei et al., 2003).

## 2.7 Rain Scattering and Absorption

Scattering is an interaction process between the path of the electromagnetic waves and rain particles (Oguchi, T., 1983). Each particle scatters energy from the incident signal and reradiates that energy in all directions, causing not only forward scatter, but also side and back scatters (Albendag & Zain, 2014) as shown in Figure 2.3. The particle will then be like an optical gap to the incident wave. The scattering occurs only when the refractive index of the particle is different to the air medium. Therefore, the scattering takes place whenever an electromagnetic wave hits the raindrop. In the atmosphere, the absorption of the higher microwave signals indicates to the size of the raindrops is close to the wavelength.

**Figure 2.3:** Raindrop scattering principle

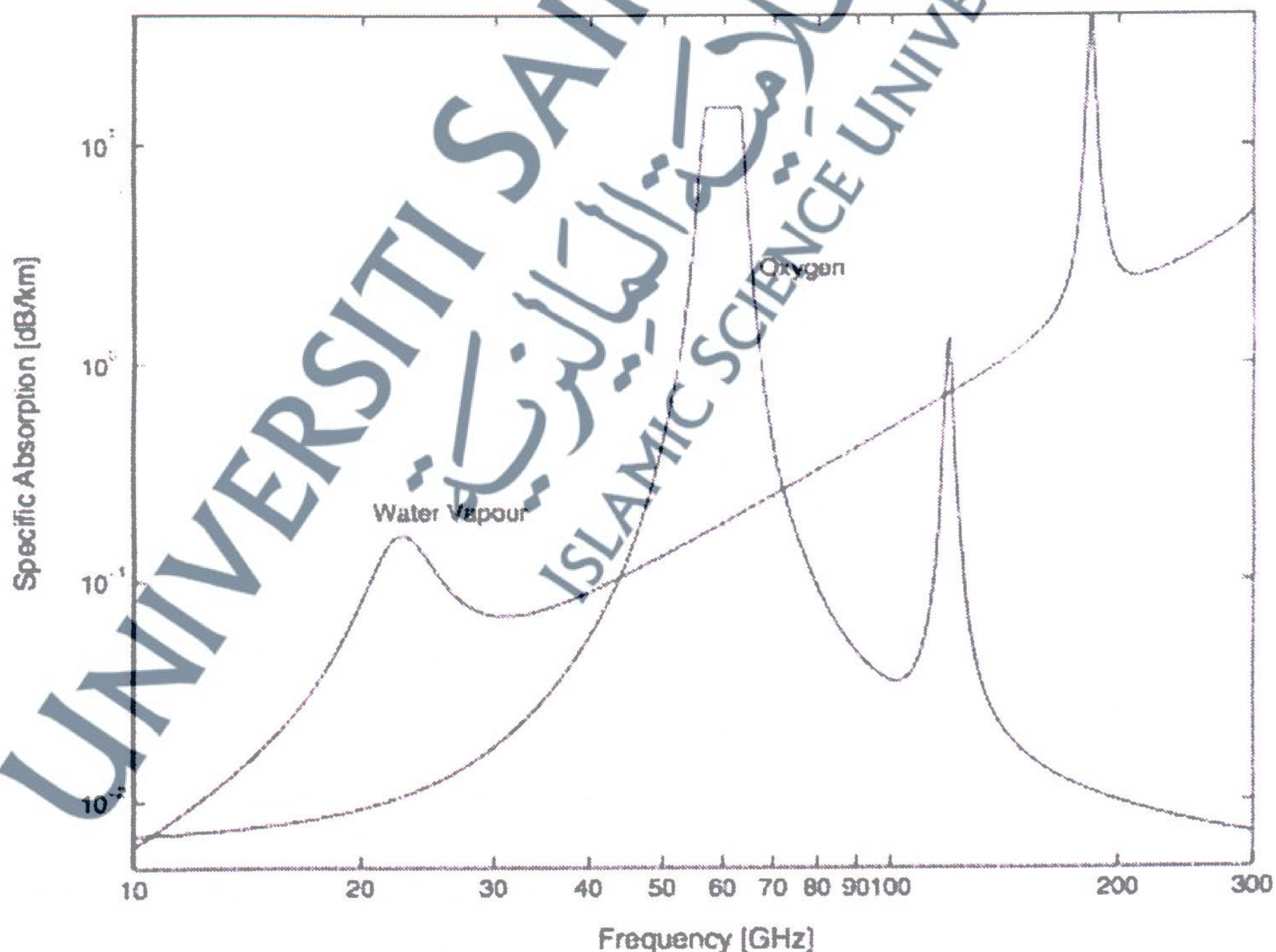




Gaseous molecules that exist in the atmosphere absorb energy from radio waves passing through them causing attenuation. This absorption is greatest due to the molecules such as water ( $H_2O$ ) and oxygen ( $O_2$ ). Each type of absorbing molecule contributes a general background level of absorption, where they are proportional non-linearly with the frequency (Hongwei et al., 2001).

Figure 2.4 shows the specific absorption [dB/km] produced by gaseous molecules. It can be seen that only  $O_2$  and  $H_2O$  contribute significantly to absorption, although other atmospheric gases may be significant in very dry air at above 70 GHz. The main resonance peaks of  $O_2$  are at 60 and 118.74 GHz, whereas those of  $H_2O$  are 22.3 and 183.3 GHz. (ITU-R, 2008).

**Figure 2.4:** Specific attenuation of water vapor and oxygen for different frequencies [ITU-R, 2014].





## 2.8 HAPS Advantages

The first advantage of using HAPS is that it can provide wide coverage. The area that can be covered by a single HAPS is equivalent to the area covered by 258 ground terrestrial towers. The possibility for takeoff and landings for maintenance and upgrading in short period of time makes the HAPS more promising technology. This technology is offering mobility, access, and coverage in urban and rural areas effectively for whole population ([www.qucomhaps.com](http://www.qucomhaps.com), 11 Dec 2014).

Moreover, the HAPS cost is lower compared to terrestrial and satellite based systems. The high bit rates, large metropolitan coverage, and the fact that the user terminals are not dependent upon a ground infrastructure, makes the HAPS a favorable technology.

## 2.9 Applications and Services

HAPS can exchange the information with numerous other stations (mobile or fixed clients, or control center applications) generally located on the ground. In addition, the information could be exchangeable between the platforms or platform and satellite. Applications and services could be related, but with a small distinction between them. An application can be considered as the end product offered to the user over which services will be used. HAPS network is a new infrastructure which can provide many applications to facilitate various applications and services which are classified as broadband or narrowband depending on the required bandwidth.

### 2.9.1 Narrowband Services

The narrowband services provided by HAPS are

1. Medical telemetry



2. Commercial applications
3. Voice telephony
4. Chat, home automation
5. Navigation and positioning
6. Traffic monitoring
7. Environmental surveillance

### 2.9.2 Broadband Services

HAPS comprehensive broadband services provide simultaneous voice and data, globally. The broadband services provided by HAPS are

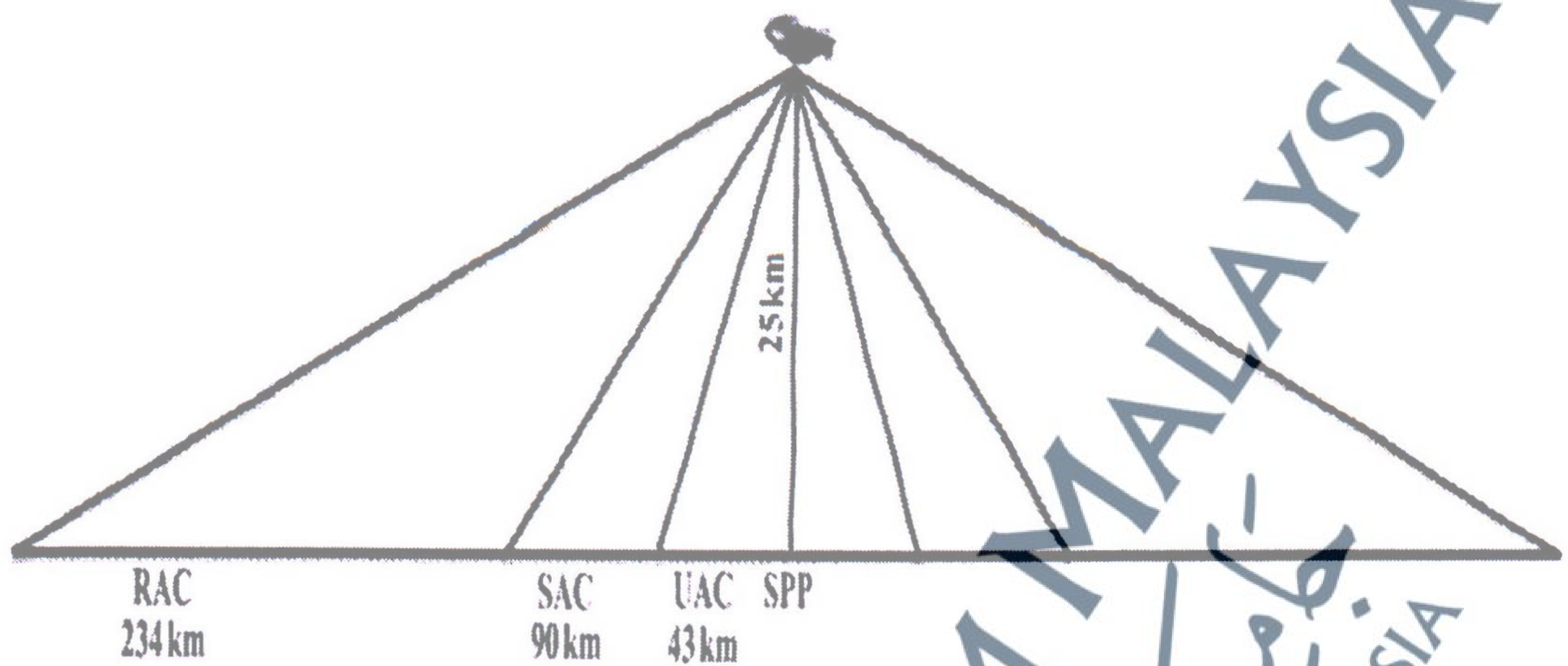
1. Conversational services (e.g. voice and video telephony)
2. Streaming services (e.g. real-time radio and television)
3. Interactive data access (e.g. the Web)
4. Background file transfers (e.g. email and File Transfer Protocol)

### 2.10 HAPS Coverage Factors

The coverage is the geographic area covered by electromagnetic waves to provide the service to the users on ground. It depends on several factors such as the antenna height, transmitted power, antenna gain as well as the radio frequency, where some frequencies can provide better regional coverage, while others can penetrate better through obstacles, such as buildings in cities. Figure 2.5 shows the ITU-R HAPS coverage, where it is divided into three coverage areas: urban (UAC), suburban (SAC) and rural area coverage (RAC). Each type of area is determined by the elevation angle of the receiver.



**Figure 2.5:** Coverage area radius in systems based on HAPS



Each stratospheric segment is able to deploy a multi-beam antenna capable of transmitting numerous spot beams within its coverage area, where the platform acts as the antenna tower located at an altitude between 17 to 25 km (Zain & Albendag, 2013).

## 2.11 HAPS Architecture

The HAPS wireless communication system is composed of two main parts (Alejandro et al., 2008)

### 2.11.1 Stratospheric Segment

The HAPS stratospheric segment contains platform requirements to establish communications with ground facilities and other HAPS, where the platform is the main part of the network. The stratospheric segment can be divided into two main elements, the payload and the bus. The payload represents the motivation for the

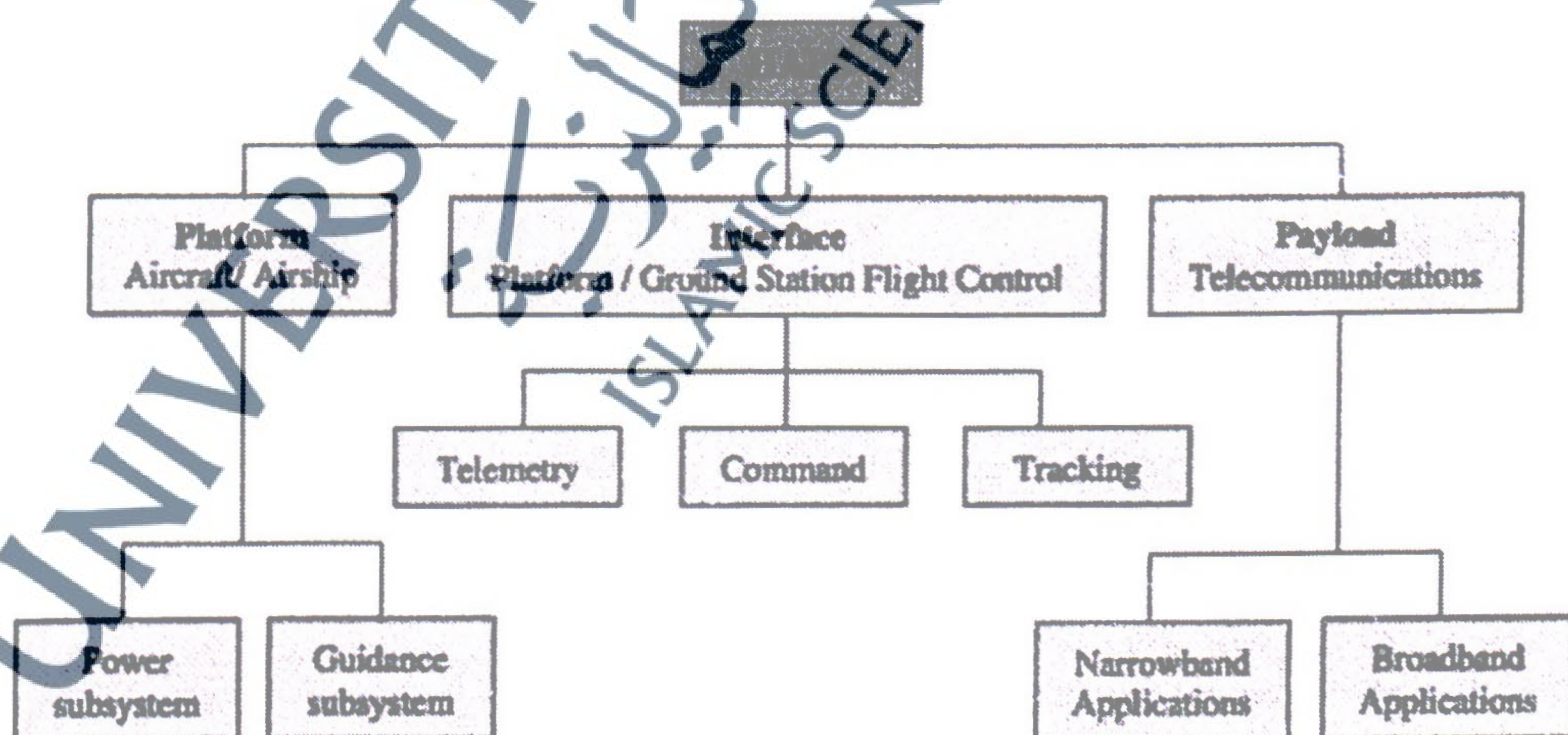


mission in terms of weight. The researches are ongoing to design a light segment to achieve the highest power consumption, where the buoyancy of the HAPS decreases in proportion to the increase of the stratospheric segment weight.

To guarantee that the stratospheric segment is ready to operate, it must to be equipped by the bus. In particular, the following points must be taken into account for obtaining the efficient HAPS service:

1. The payload must be placed in the correct position, so that coverage is directed to the users.
2. The payload should be in the exact altitude to cover the whole area.
3. The data from the payload should be transmitted to the ground stations and vice versa.
4. The payload must operate for the longest period of time
5. The energy source must be provided to enable all payload functions to be performed. The HAPS subsystems are shown in Figure 2.6.

**Figure 2.6:** Subsystems of the HAPS stratospheric segment [Grace, D., & Mohorcic, M. 2007]





### **2.11.1.1 Platforms**

HAPS can be classified as an airship or aircraft (manned or unmanned) placed in the stratosphere layer (17 to 25 km). A stratospheric platform dimension and weight depends on the stratosphere's environmental conditions, such as atmospheric pressure, humidity, air density, and wind speed. All of these items have an impact on the buoyancy of the HAPS.

Both types of HAPS can be powered by different power sources, such as fuel, electric motors or solar energy. The preferred form of power source is the sun in terms of the cost and the efficiency.

### **2.11.1.2 Telecommunications Payload**

The telecommunications payload consists of phased transceiver array antennas (Al-Samhi & Rajput 2012) for sky-to-ground (downlink) or ground-to-sky links (uplink), and a very large bank of processors that handle the physical layer operations such as transmitting, receiving, multiplexing and switching.

The HAPS communication system could be designed to operate as stand-alone infrastructure or it could be integrated with a network that employs traditional terrestrial base station towers to exchange the data with users (Pinkney, 1997). The payload subsystem must be compatible with the services and the frequency bands regulated by national and international telecommunications authorities.

### **2.11.1.3 Telemetry**

The telemetry subsystem has the responsibility of the interface between the platform and the ground station flight control, where it supports the function of stratospheric segment management.



These functions are the main guarantee of success the operation of the HAPS. The main functions of a telemetry system are to:

1. Monitor the performance of the payload and transmit the monitored data to the ground control center.
2. Measure the environment parameters.
3. Provide the exact position to earth stations for tracking.
4. Receive commands from the ground control center for performing various functions of the HAPS.

The other function of the telemetry subsystem is to monitor the HAPS power source parameters such as voltage, current, temperature and equipment status and transmit the measured values to the ground control center. The links between the stratospheric segment and the Control Station must be in a direct LOS condition.

#### **2.11.1.4 Command**

The command system receives the commands transmitted from the control center, verifies the receptions and executes dedicated commands. Examples of common commands are:

1. Altitude and position switching
2. Switching diversity method
3. Antenna pointing control
4. Controlling direction and speed
5. Power source switching
6. Signal power control



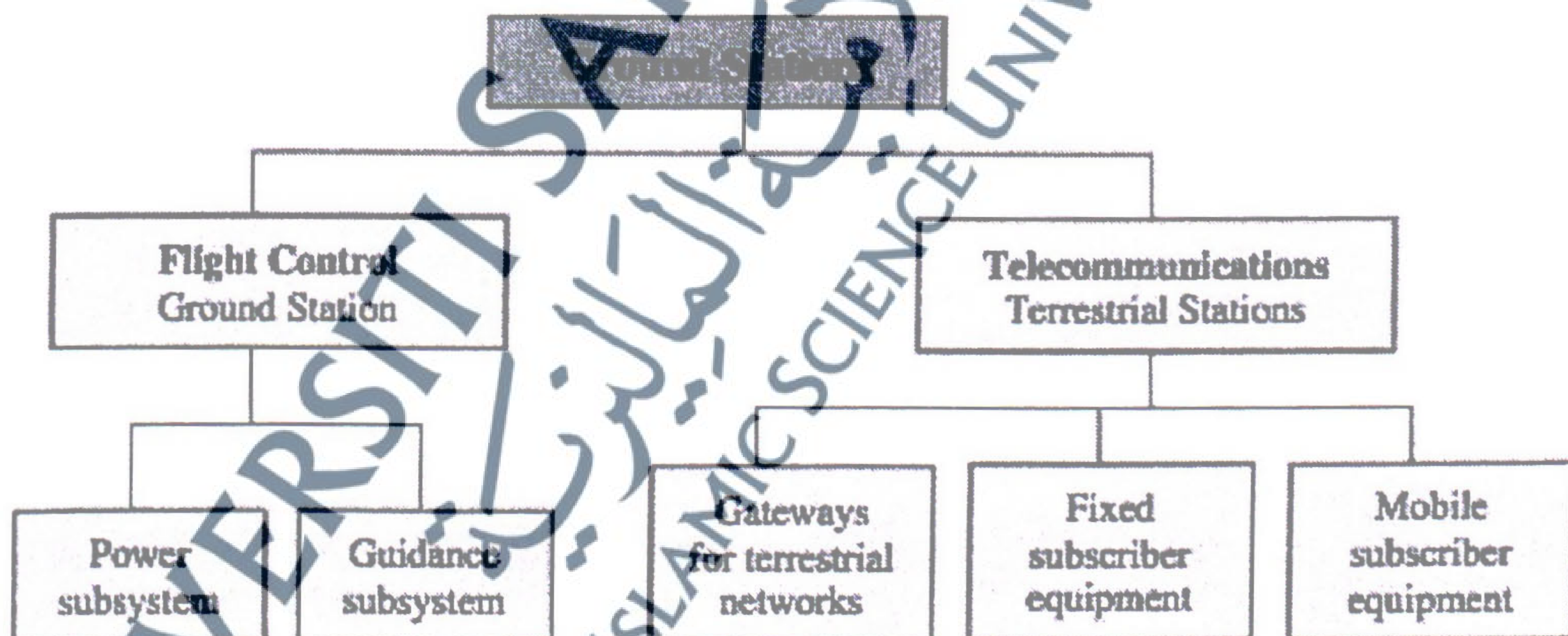
### 2.11.1.5 Tracking

The tracking system is used to maintain the HAPS in its assigned position and altitude to cover a specific area on earth, to decrease the bit error rate and to deliver the data to the ground segment with the highest signal power ensuring the LOS transmission.

### 2.11.2 Ground segment

The ground segment of HAPS is responsible for the data exchange between the stratospheric segment and the users on the ground as well as to control some commands related to the HAPS operations mentioned earlier. The ground stations should be equipped with proper transceivers to send and/or receive the data from or to the HAPS as well as to communicate with the equipments of the payload. The main ground segment functions are shown in Figure 2.7.

**Figure 2.7:** HAPS ground segment subsystem [Grace, D., & Mohorcic, M. 2007]



1. Tracking to HAPS position determination
2. Telemetry to analyze and record HAPS received data
3. Commanding to control HAPS equipments
4. Communication links to other worldwide ground stations, gateways and local



fixed or mobile subscribers.

## 2.12 Malaysian Activities on HAPS

Several countries have recently undertaken the activities on HAPS as a promising technology for the future of communications infrastructure worldwide. This section highlights the HAPS project and activities in Malaysia.

ICT Infrastructural development in Malaysia has accelerated dramatically in urban areas while large tracts of rural areas remain un-served largely due to the prohibitive cost of building communication infrastructure. The Malaysian sky station (M-55) was announced in March 2007 with the objective of bringing HAPS technology to Malaysia to establishing the HAPS project. The goal of this mission is to provide wireless communication services, especially for rural and remote areas (Geoscan. et al., 2004; ). However, the QucomHaps expertise will enable the Malaysian ICT sector to tap into an additional layer of communication infrastructure in order to provide connectivity to all areas at considerably less cost compared to other terrestrial and satellite services and expanding their services nationwide.

Within Malaysia, there are multiple market opportunities that can be serviced by this technology including:

1. Telecommunications (broadcasting, voice, data, video)
2. Emergency services/Disaster Relief communications
3. Surveillance
4. Coastal and climate monitoring

For these potential uses, the telecommunications services may have the largest impact in this project since the Malaysian government is seeking solutions to provide



broadband services to the whole areas, which may not be covered by the National Broadband Network.

The ability to cost-effectively deliver services to underserved rural and remote areas within Malaysia makes HAPS the best choice for the telecommunication technologies.

### **2.13 HAPS Network**

Stratospheric platforms are known as infrastructure able to integrate multiple general services. HAPS can play the same role as satellite communication, with the major advantages of being less expensive, closer to the ground, movable on demand, and easy to maintain. The deployment times of communication systems based on HAPS are substantially less than satellite or terrestrial systems (Djukanic et al., 1997).

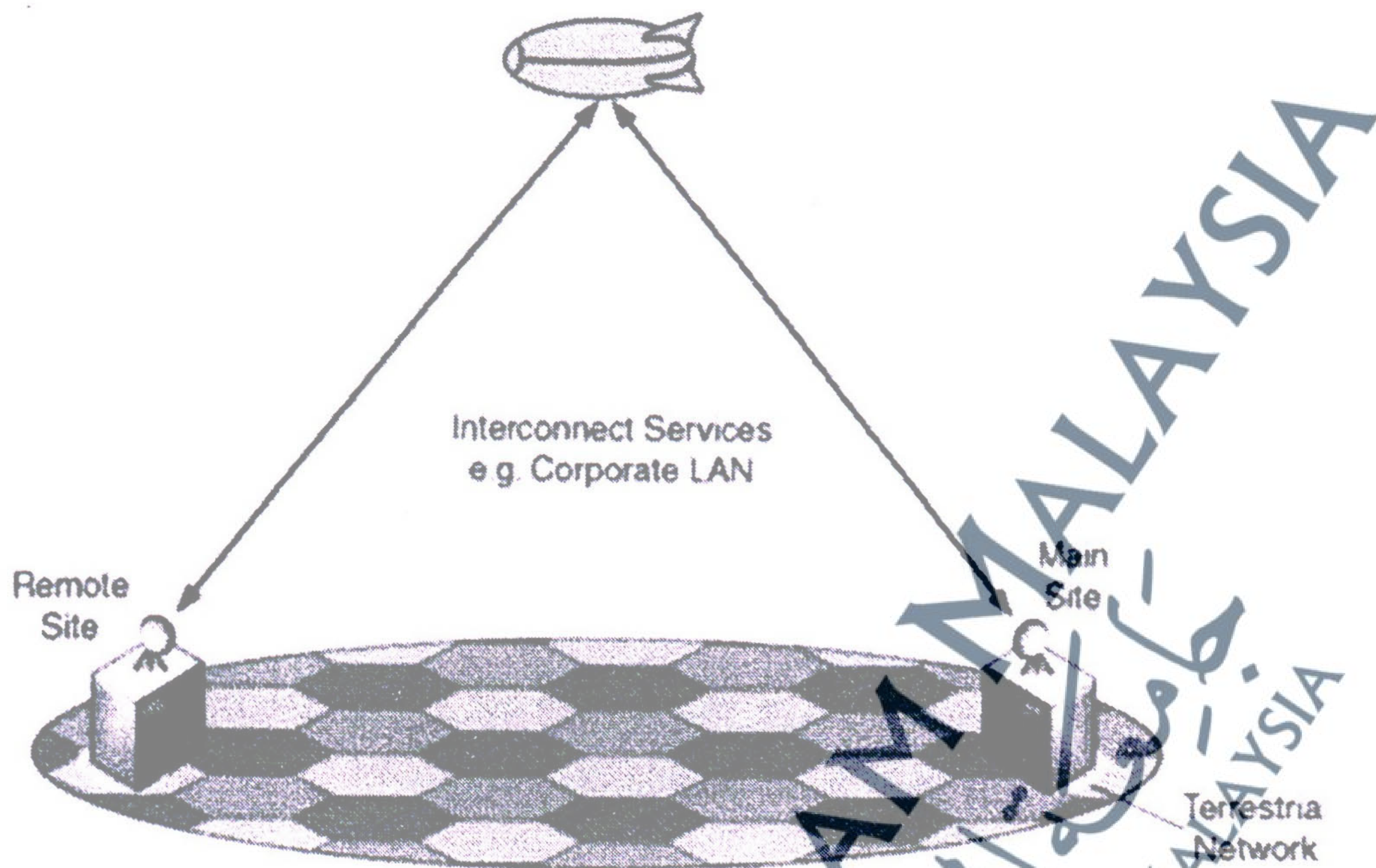
HAPS can operate as standalone or it can be interconnected to external networks via gateways. The different design characteristics yield three main network architecture scenarios, which are explained in the next subsections.

#### **2.13.1 Standalone Platform Links**

A standalone HAPS network connection used to deploy a basic coverage or additional temporary events such as sports events or disaster relief operations where the terrestrial infrastructure may not be readily available for switching on the ground. The stand-alone scenario shown in Figure 2.8.



**Figure 2.8:** Stand-alone HAPS network [Grace, D., & Mohorcic, M. 2007]



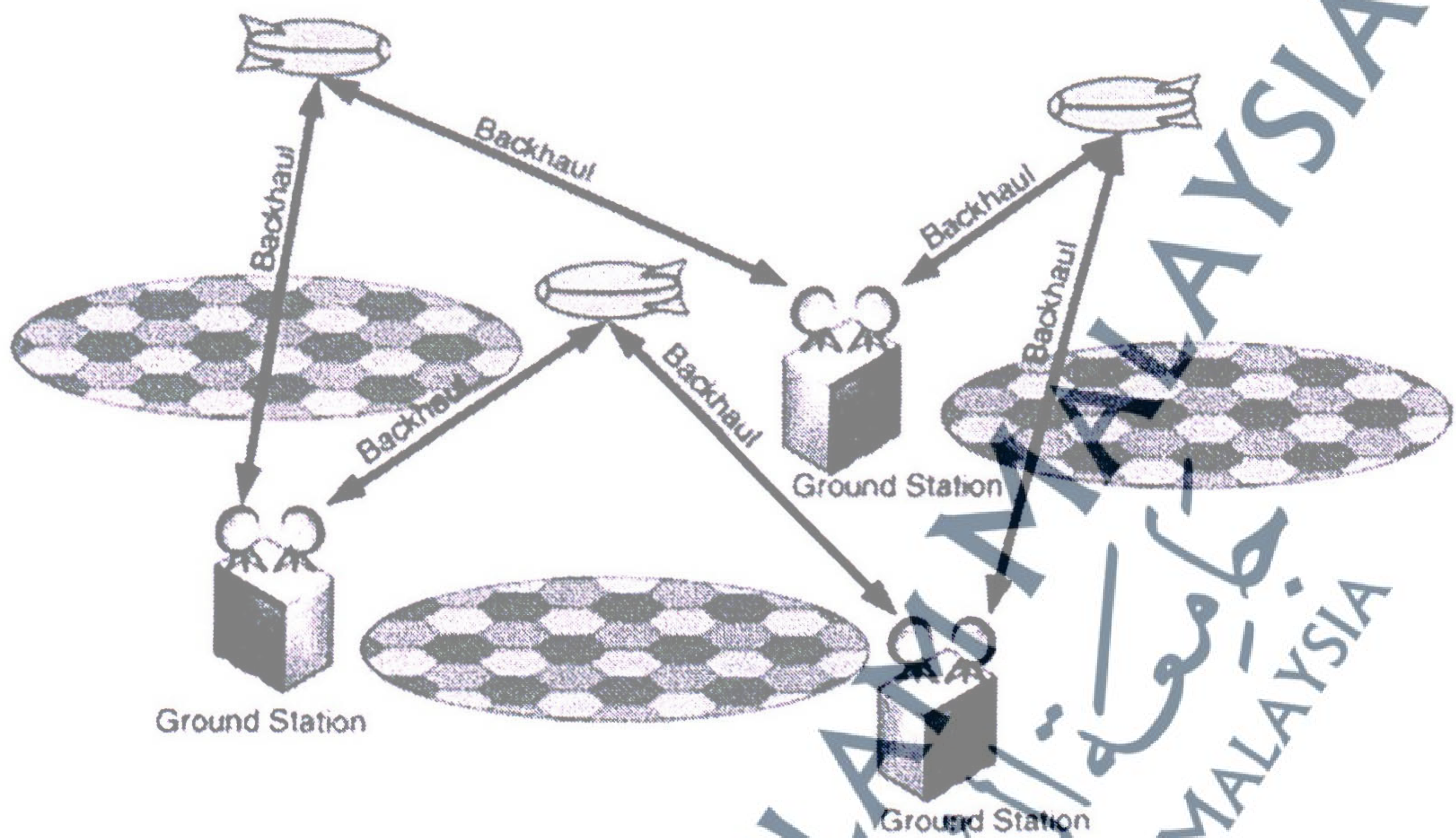
In the HAPS standalone scenario, the capacity is limited to communicate between the users within the same platform coverage area, or with other networks in the ground connected to the HAPS.

### 2.13.2 Platforms Connected via Ground Stations

Other network scenarios using several platforms are possible (Kandus et al., 2005). In the case of multi-platform HAPS, ground stations or inter-platform links (IPL) can be used as a relay between two HAPS dependent on the segment facilities as shown in Figure 2.9. Switching can be on the ground or onboard. The advantage of onboard switching is the improvement of the service quality between the communicating parties within the same platform coverage area, while the ground switching has the advantage of weight reduction of platform payload and power consumption.



**Figure 2.9:** HAPS interconnected using ground stations [Grace, D., & Mohorcic, M. 2007]

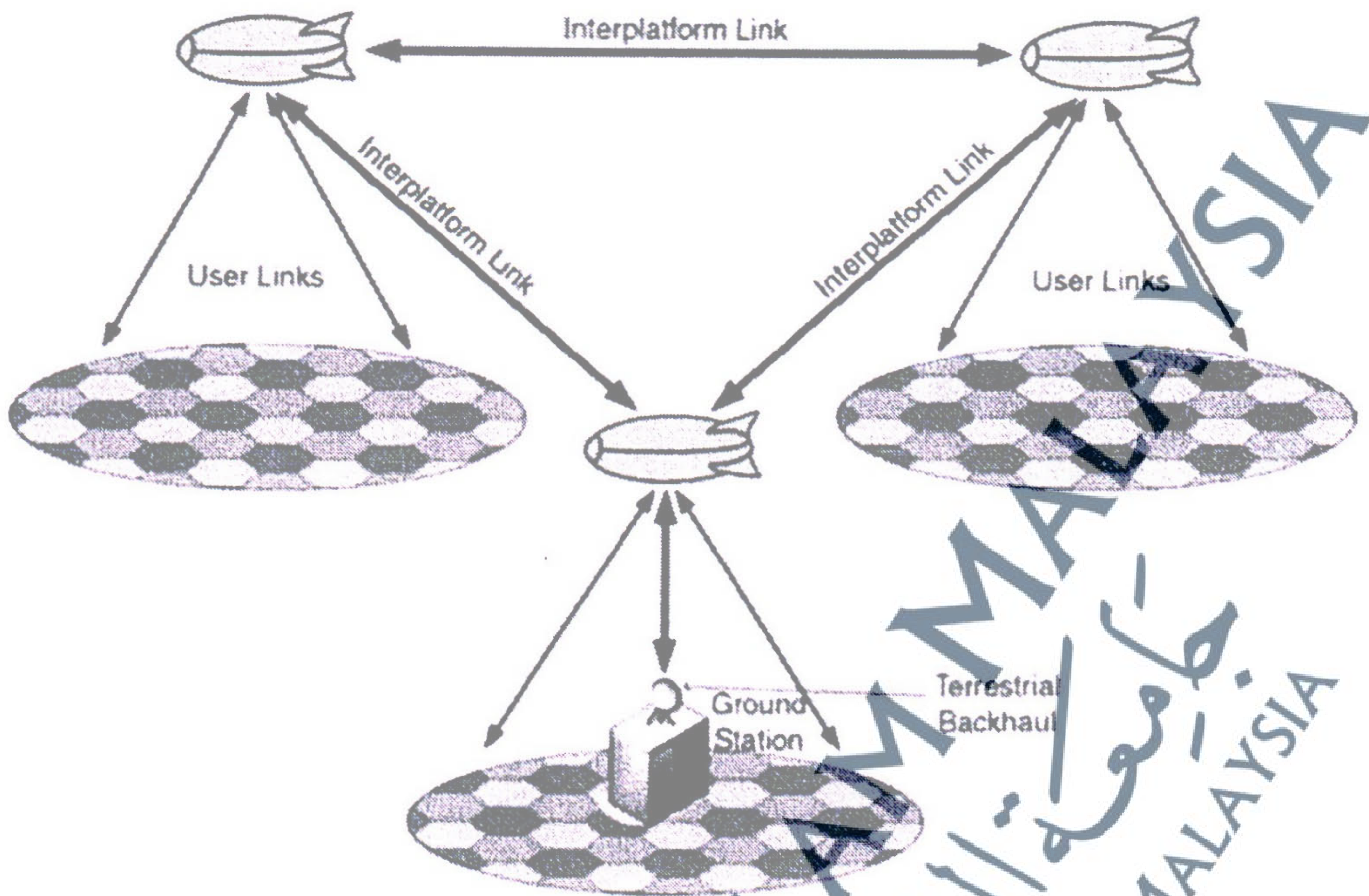


### 2.13.3 HAPS Interconnection via IPLs

The HAPS Interconnection via IPLs scenario is depicted in Figure 2.10. In this case, the system contains two or more platforms. Each HAPS payload includes a switching device and one or more IPL transceivers to be able to communicate between adjacent platforms without any terrestrial elements needed.



**Figure 2.10:** Interconnection of HAPS via IPLs [Grace, D., & Mohorcic, M. 2007]



In this scenario, ground stations can be gateways to other public and/or private networks. There are numerous advantages of using IPL versus a ground station connection. The first advantage is that the system is independent from terrestrial infrastructure. As a result, a highly flexible system is expected and the requirements of the system for up and downlink were reduced as well as the low signal delay.

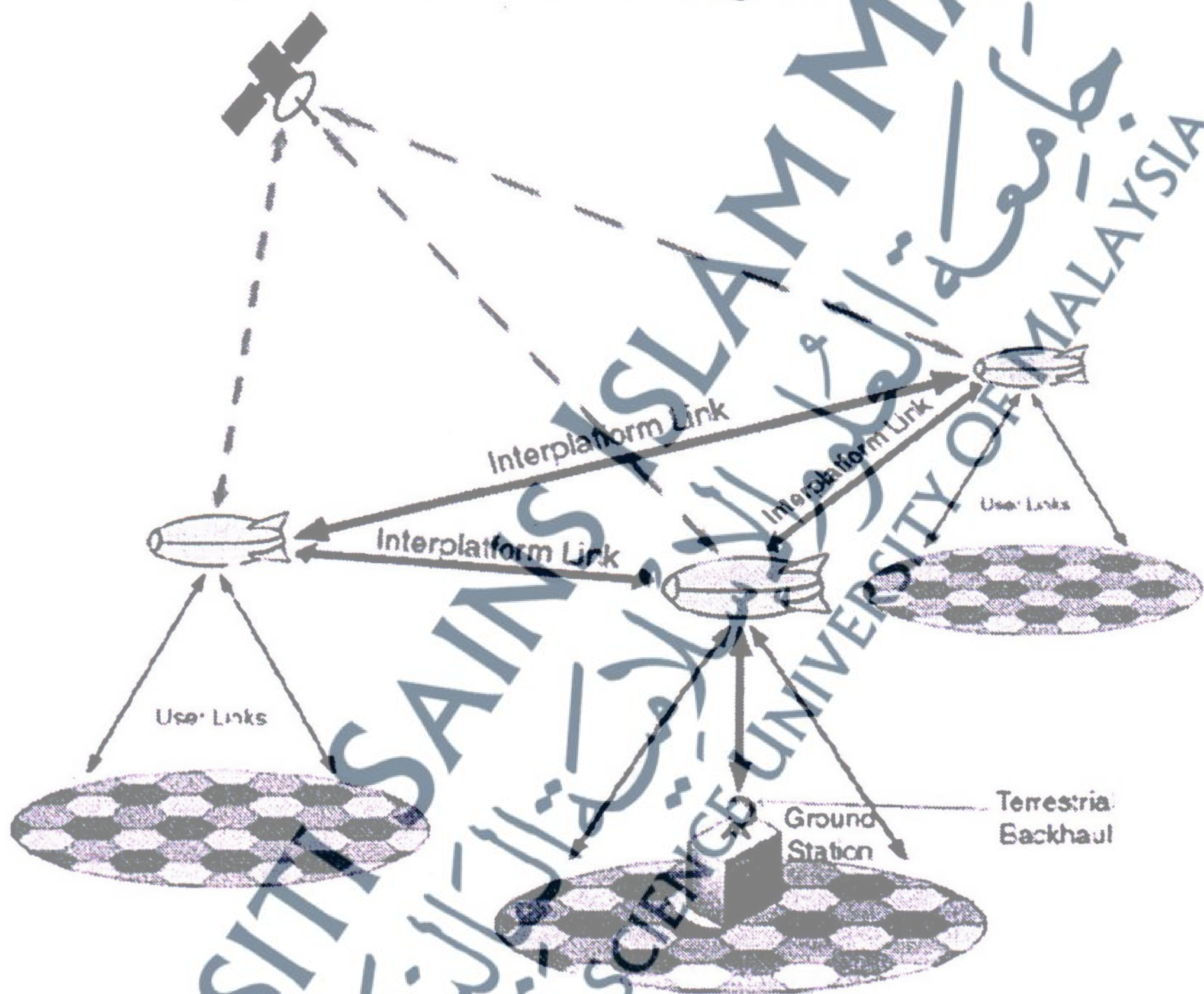
#### 2.14 HAPS-Satellite Integration

HAPS is intended to act as a relay station. The HAPS network can include a number of HAPS depending on the size of the area. In general, the lower the elevation angle for the HAPS, the larger the coverage. In practice, the minimum elevation angle for wireless communication implies that for a platform placed at an altitude of 25 km, the area that be covered is approximately 490 km. HAPS can intercommunicate through



the scenarios mentioned in the subsections above (Section 2.13.1 through Section 2.13.3). HAPS also can be connected through one or more satellites creating a hybrid HAPS-Satellite communication network as shown in Figure 2.11. For remote areas where there is no substantial terrestrial infrastructure, satellites can be used as backhaul.

**Figure 2.11:** HAPS network integrated to satellite



As integrated stand-alone scenarios, HAPS and satellite systems can represent a complete infrastructure for wireless communications, to provide telecommunication capabilities for narrow and broadband services. Nevertheless, each of the two technologies can efficiently help each other to reduce the impact of the performance limitations. The HAPS can act as an intermediate layer for providing the services, which can greatly reducing physical layer requirements for the earth station while the satellite can be effectively used to interconnect HAPS platforms. The satellite can



enhance the actual coverage capability by connecting the HAPS with a very remote location. For these and other reasons, an integrated architecture looks very attractive to achieve the daily demands in the wireless communication field.

## 2.15 Satellite Systems

Three types of satellite systems are shown in Figure 2.12, where they currently used for providing different communication services. The fundamental differences are include the altitude as well as the coverage footprint on the earth.

**Figure 2.11: Orbits of Satellite Systems**



### 2.15.1 Low Earth Orbit Satellite Systems

A LEO satellite system consists of a group of satellites in circular orbits, at altitudes between 200-2000 kilometers (Liu & David, 2009). LEO systems have several advantages such as the cost. This is because the launching complexity is lower than the others. Since the LEO system is located at a lower altitude, it has less free space



loss and fewer propagation delays. Therefore, the power consumed for both satellite and ground stations are a minimum. Because of the lower altitude, the rotation speed for LEO systems must be higher to maintain their orbits. One of the disadvantages of LEO is that the footprint on the earth is smaller where it has a diameter of approximately 8000 km. LEO satellites are typically used for providing GPS, cellular communication services and the global mobile communications.

### **2. 15.2 Medium Earth Orbit Satellite Systems**

The medium-earth orbit system is a compromise between LEO and GEO systems. A MEO satellite is located at an altitude of about 10,000 km (Kota, 2004). The propagation delay, power requirements and antenna gains are much higher than the LEO system due to the higher altitude. The MEO system is called a polar orbit because it rotates around the poles of the earth. Polar orbits have the advantage of covering different sections of the earth's surface as it is rotating around the earth. MEO systems are not preferred for commercial uses due to budget cuts.

### **2. 15.3 Geostationary Satellite Systems**

The satellites of these systems are located at an orbit altitude of about 36,000 km (Iida, 2000). A GEO satellite can cover very wide areas and a few satellites are enough to provide worldwide coverage. Since GEO satellites are maintained stationary, the ground antennas could be pointed to a fixed position. However, geostationary satellites have several disadvantages such as the high cost of placing the satellite in the orbit, significant propagation delay due to the height, the on board segment requirement of a high power transmitter to relay information back to earth, and a high EIRP that is required at the earth stations.



## 2.16 Rain Attenuation

The rain prediction models are discussed in this chapter. This chapter demonstrates the derivation of the mathematical equations that were used for the rain attenuation models. The basic principle of rain and the rain attenuation models are discussed in the first part of this chapter.

This chapter also explains in detail, the proposed rain attenuation models that have been used to carry out this study. The new model which able to predict the rain attenuation for the non-geostationary satellites is also included in this chapter. The chapter is also discusses the new method that is able to calculate the effective rain cell size which affects the signal path based on the relative cloud velocity.

### 2.16.1 Rain Rate

Rain rate  $R$  is a measure of the intensity of rain by calculating the volume of rain that falls on the ground in a certain period of time. The rain rate is expressed in units of length (depth) per unit time (mm/hr), which is the depth of rain captured by a collection vessel per unit time.

The relation between the rainfall rate  $R$  and the drop size  $D$  is given by

$$R = \frac{6\pi}{10^4} \int_0^{\infty} v(D) D^3 N_D dD \quad [\text{mm/hr}] \quad (2.1)$$

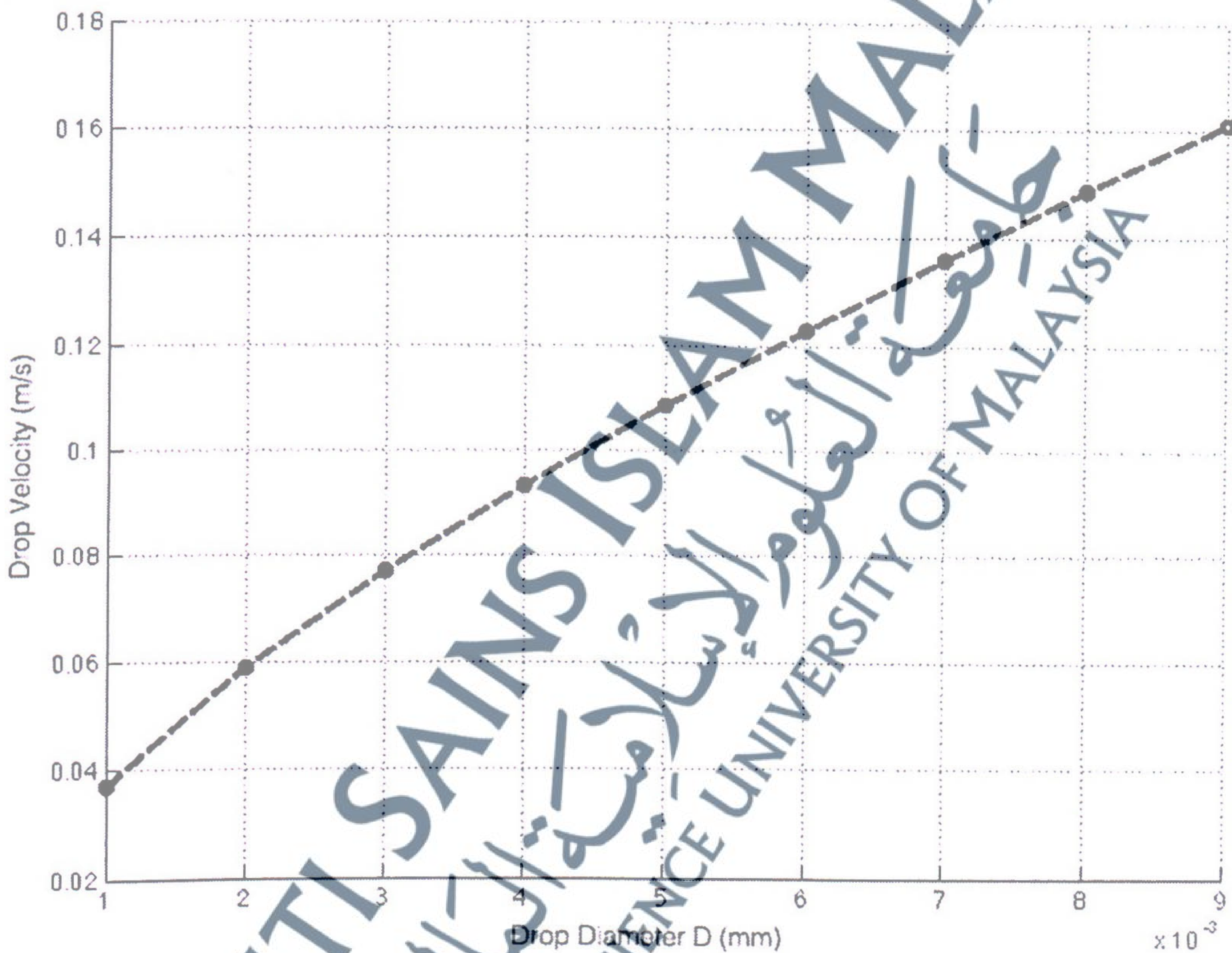
The relationship between drop velocity and drop size can be obtained by (Ulbrich, 1983).

$$v(D) = 3.78D^{0.67} \quad (2.2)$$



where  $v(D)$  represents the relationship between the raindrop terminal fall velocity in the air per meter (m) and the raindrop diameter  $D$  (mm). As drop size increases, the falling drop velocity increases rapidly following the curve, as shown in Figure 2.13, where it is plotted based on Equation 2.2.

**Figure 2.13:** Behavior of raindrop velocity based on drop radius



The drop fall speed in other models is calculated based on the air pressure, while this issue is not considered in this study.



## 2.17 Rain Attenuation models

Many models have been proposed to determine the rain attenuation such as the Lin model (Lin, S. H., 1979), Dutton-Dougherty model (Dutton et al., 1982), the Simple Attenuation model (SAM) (Stutzman & Yon, 1986), the Global model (ITU-R, 2014), Crane model (Crane, 1971), and the CCIR model (CCIR, 1984). This study presents an evaluation of the HAPS channel to identify the best HAPS location in the peninsular of Malaysia based on the modified ITU-R model. ITU-R is globally agreeable, where it is capable to predicts the rain attenuation for different environments. It was tested against available data and has been shown to yield an accuracy that is both compatible with the natural variability of propagation phenomena and adequate for most present applications in system planning (ITU-R, 2010).

The ITU-R model consists of two main factors, as follows.

$$A_{0.01} = \gamma_R \times L_E \quad [dB] \quad (2.3)$$

$$\gamma_R = k(R_{0.01})^\alpha \quad [dB/km] \quad (2.4)$$

where:

$A_{0.01}$  is the predicted attenuation exceeded 0.01% of time in average year.

$\gamma_R$  is the specific attenuation (dB/km) obtained from the rain rate of 0.01% of time in the average year.

$R_{0.01}$  is the rainfall rate exceeded for 0.01% of time in average year.

$L_E$  is the effective path length in km.



The first factor is the specific attenuation while the second parameter is the effective path length of the signal affected by the rain.

### 2.17.1 Specific Attenuation

This parameter is a key element in calculating the total rain attenuation as shown in the ITU-R P618-9 rain prediction model (ITU-R, 2009). It is commonly used for the rain attenuation prediction per unit distance. The relationship between the rain attenuation [dB/km] and rainfall rate is shown in Figure 2.14.

Several experimental measurements have been carried out by many researchers to find the relationship between rainfall and attenuation. They yielded the formula illustrated in Equation 2.5, where the values of  $k$  and  $\alpha$  are obtained from the curve fitting of the experimental results (Crane, 1971).

$$\gamma_R = kR^\alpha \quad (2.5)$$

These coefficients are determined as functions of polarization and frequency for the range between 1 to 1000 GHz (Ong & Shan, 1997), as shown in Table 2.1. The subscripts  $V$  and  $H$  refer to vertical and horizontal polarizations respectively.  $k$  and  $\alpha$  can be calculated using Equation 2.6 and Equation 2.7.

$$k = \frac{[k_H + k_V + (k_H - k_V)\cos^2\theta\cos 2\tau]}{2} \quad (2.6)$$

$$\alpha = \frac{[k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos 2\tau]}{2k} \quad (2.7)$$



where:

$\theta$  is the path elevation angle.

$\tau$  is the polarization tilt angle relative to the horizontal ( where  $\tau = 45^\circ$  for circular polarization).

$R$  is the rain rate in mm/h.

$k$  and  $\alpha$  are power law parameters, which depend on polarization and frequency  $f$  (GHz), in the range from 1 to 1000 GHz (ITU-R, 2013).

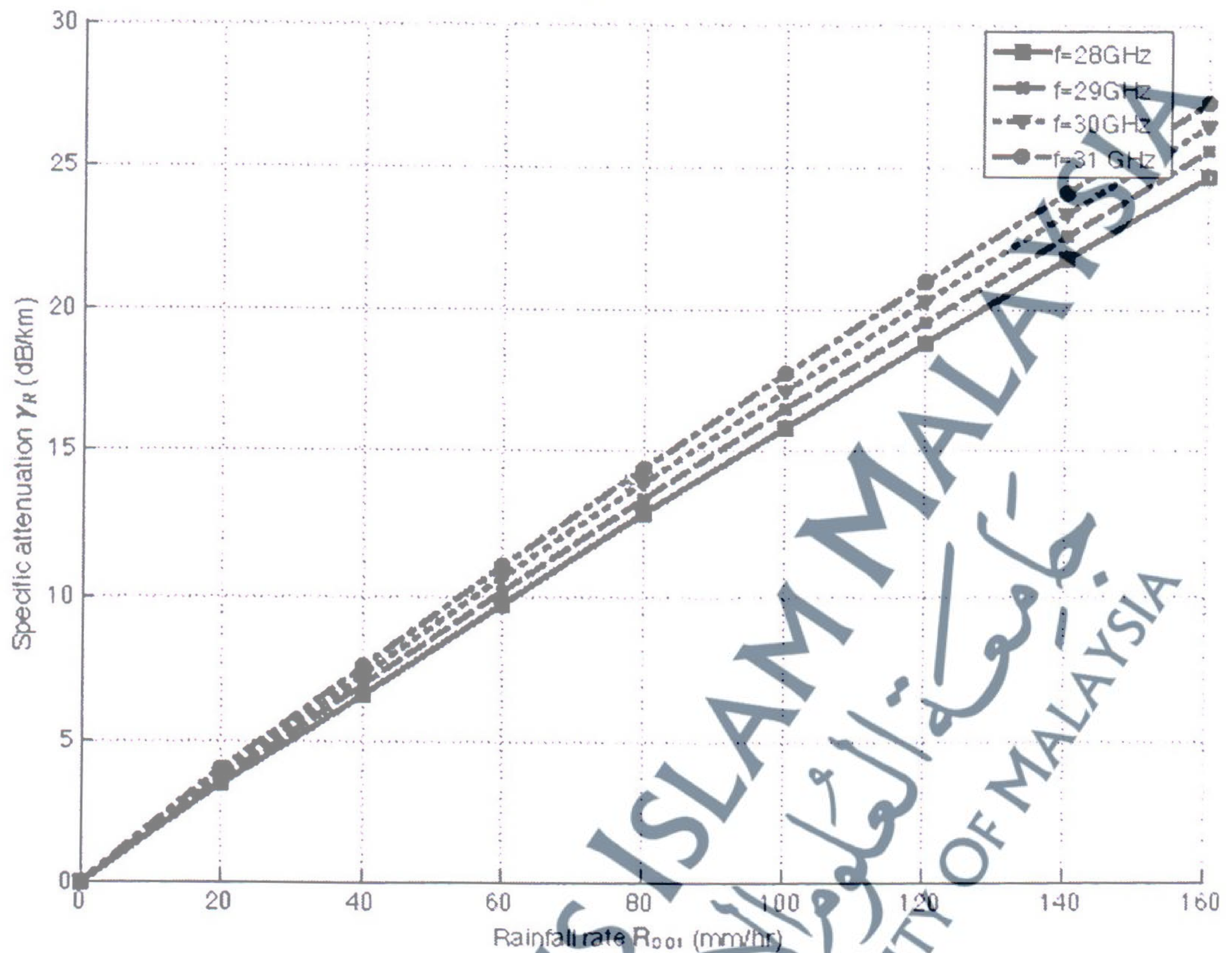
**Table 2.1:** Vertical and horizontal parameters for  $K$  and  $\alpha$

| Frequency<br>(GHz) | $k_H$  | $\alpha_H$ | $k_V$  | $\alpha_V$ |
|--------------------|--------|------------|--------|------------|
| 28                 | 0.2051 | 0.9679     | 0.1964 | 0.9277     |
| 31                 | 0.2588 | 0.9392     | 0.2465 | 0.9055     |

The specific attenuation as a function of the rainfall rate for different frequencies is illustrated in Figure 2.14, where the results shown in the figure was calculated based on Equation 2.5. It is can be noted that the increase in the specific attenuation is about 9 times when the HAPS downlink signal passing through a rain cells from 20 to 160 mm/hr. The attenuation is more significant with high rain rates and higher frequency.



**Figure 2.14:** Relationship between specific attenuation and rainfall rate for different frequencies



The attenuation is predicted based on the ITU-R model, which is given by ITU-R Rec. number P.838-3. The result is based on 0.01% of average time of rainfall rate from 0 to 160 mm/hr, which is reasonable for a tropical area such as the peninsular of Malaysia.

### 2.17.2 ITU-R Rain Attenuation Model

When Olsen initially proposed the statistical rain attenuation model in the Communication Research Center (CRC) in 1978, a prediction equation was developed to estimate the rain attenuation quantity for any rainfall rate  $R$  [mm/hr] (Choi et al., 2011).



$$A_{0.01} = \gamma_R L_E \quad [\text{dB}] \quad (2.8)$$

Where the specific attenuation  $\gamma_{0.01}$  is a function of the intensity of the rainfall rate.

$$\gamma_{0.01} = kR^\alpha \quad [\text{dB/km}] \quad (2.9)$$

$A_{0.01}$  is a predicted attenuation that is exceeded 0.01% of the time in average year, while  $\gamma_R$  is the amount of rain attenuation [dB] per unit length [km] for any rainfall rate amount. Where it is dependent on the frequency and polarization (Jey et al., 1990).  $L_E$  stands for the effective path length that penetrated in the rain [km].

The height of the rain ( $h_R$ ), which is shown in Figure 2.15 by the dashed line, is a function of the ground station latitude. The rain height is obtained by

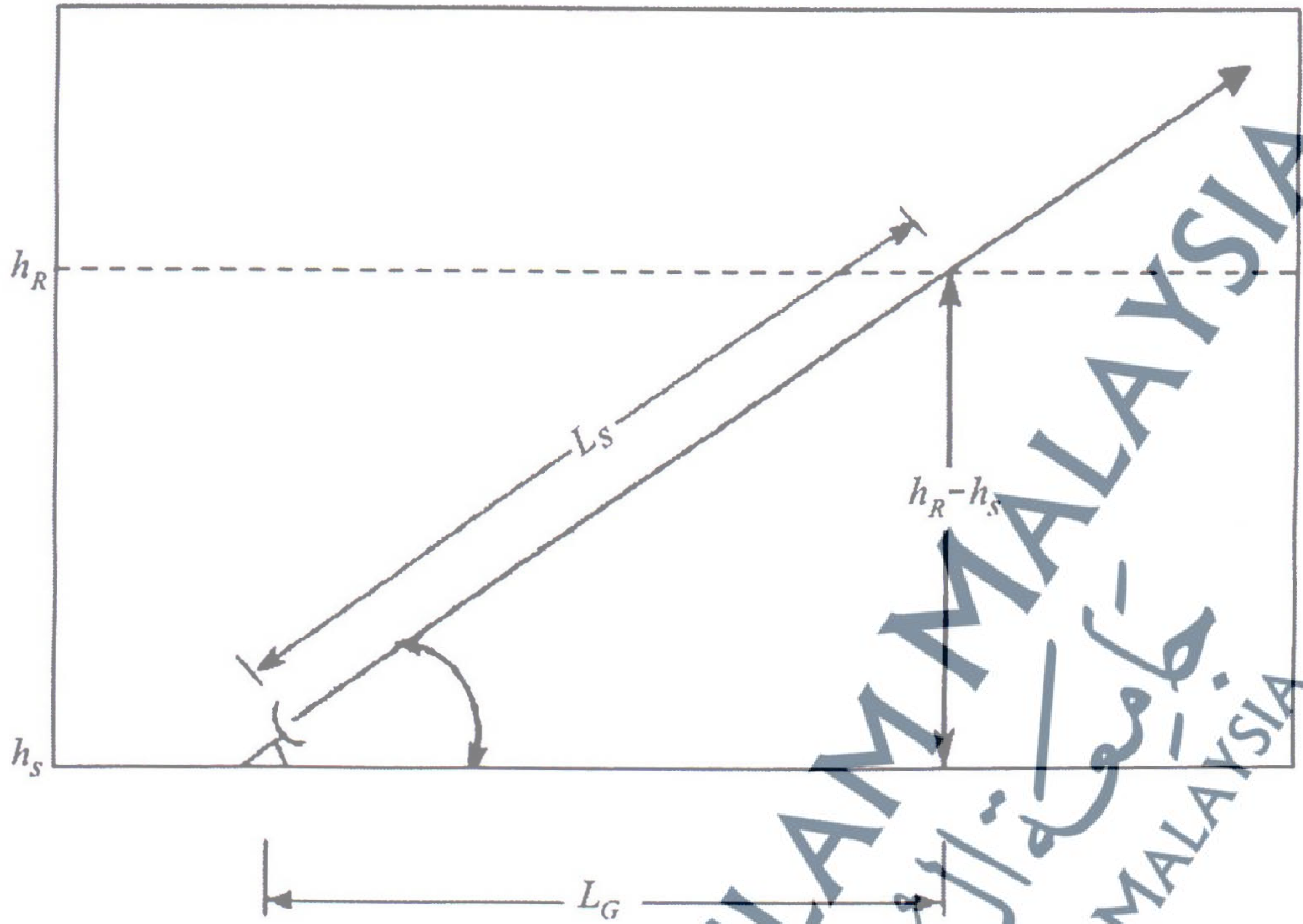
$$h_R = h_0 + 0.36 \quad [\text{km}] \quad (2.10)$$

where  $h_0$  is the mean isotherm height above mean sea level  $0^\circ\text{C}$ .

The temperature is a function of the altitude, where it decreases as the altitude increases until reaching the freezing layer height. The cloud's impact is assumed to be absent because it exists above the zero degree isotherm and produces much less attenuation compared with the rain.



**Figure 2.15:** Slant-path geometry for ITU-R model [ITU-R. 2009]



The length of the slant path under the rain ( $L_S$ ) is a very important parameter to predict the attenuation into a certain area, where it given by

$$\text{For } \theta \geq 5^\circ, \quad L_S = \frac{(h_R - h_S)}{\sin \theta} \quad [\text{km}] \quad (2.11)$$

Taking into account the earth curvature, the accurate slant path length estimation when  $\theta < 5^\circ$  can be obtained as follows

$$\text{Else,} \quad L_S = \frac{2(h_R - h_S)}{\sin^2 \theta + \frac{2(h_R - h_S)}{R_e}} \quad [\text{km}] \quad (2.12)$$

where:

$h_S$  is the height above mean sea level of the earth station (km).



$h_R$  is the rain height (km).

$\theta$  is the elevation angle (degrees).

$R_e$  is the effective radius of the Earth (8500 km).

$f$  is the operation frequency (GHz).

$\varphi$  is the latitude of the earth station (degree).

The horizontal projection of the slant path  $L_G$ , can be obtained from

$$L_G = L_S \cos \theta \quad (2.13)$$

The nature of the rain is not distributed equally over the geographical area of interest. In some cases, it is heavy in the center of the rain cell and decreases gradually toward the edges. To predict the rain attenuation accurately, the rain reduction factor which used to account for the rain inhomogeneity along the propagation path is needed to be calculated (Ulaganathan et al., 2011; Khamis et al., 2005).

The ITU-R 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 ( $L_S$ ). The ITU-R model utilizes a vertical adjustment factor and a horizontal reduction factor  $v_{0.01}$  and  $r_{0.01}$  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 horizontal reduction factor is given by [ITU-R. 2009]

$$r_{0.01} = \frac{1}{1 + 0.78 \sqrt{\frac{L_G \gamma_R}{f}} - 0.38 (1 - e^{-2L_G})} \quad (2.14)$$



$$\zeta = \tan^{-1} \left( \frac{h_R - h_s}{L_G r_{0.01}} \right) \quad [\text{degree}] \quad (2.15)$$

$$\text{For } \zeta > \theta, \quad L_R = \frac{L_G r_{0.01}}{\cos \theta} \quad [\text{km}] \quad (2.16)$$

$$\text{Else,} \quad L_S = \frac{(h_R - h_s)}{\sin \theta} \quad [\text{km}] \quad (2.17)$$

$$\text{If} \quad |\varphi| < 36^\circ, \chi = 36 - |\varphi| \quad [\text{degrees}] \quad (2.18)$$

$$\text{Else,} \quad \chi = 0 \quad [\text{degrees}] \quad (2.19)$$

The vertical reduction factor is given by [ITU-R. 2009]

$$V_{0.01} = \frac{1}{1 + \sqrt{\sin \theta} \left( 31 \left( 1 - e^{-\left( \frac{\theta}{1 + \chi} \right)} \right)^{\frac{\sqrt{L_R \gamma_R}}{r^2} - 0.45} \right)} \quad (2.20)$$

The effective path length ( $L_E$ ) of the signal is computed by multiplying the actual path penetrated in the rain by the vertical adjustment factor ( $V_{0.01}$ ).

The effective signal length that passes through the rain can be obtained by multiplying the physical path by the vertical adjustment factor as shown in Equation 3.19:

$$L_E = L_R V_{0.01} \quad [\text{km}] \quad (2.21)$$

Finally, the predicted attenuation of the signal exceeded for 0.01% of an average year is obtained from [ITU-R. 2010]

$$A_{0.01} = \gamma_R L_E \quad [\text{dB}] \quad (2.22)$$



The attenuation predicted based on this model is applicable for any annual average time of rainfall rate. A flow chart representing the ITU-R model is shown in Figure 2.16-A to Figure 2.16-C.





Figure 2.16-A: Flowchart design for ITU-R model

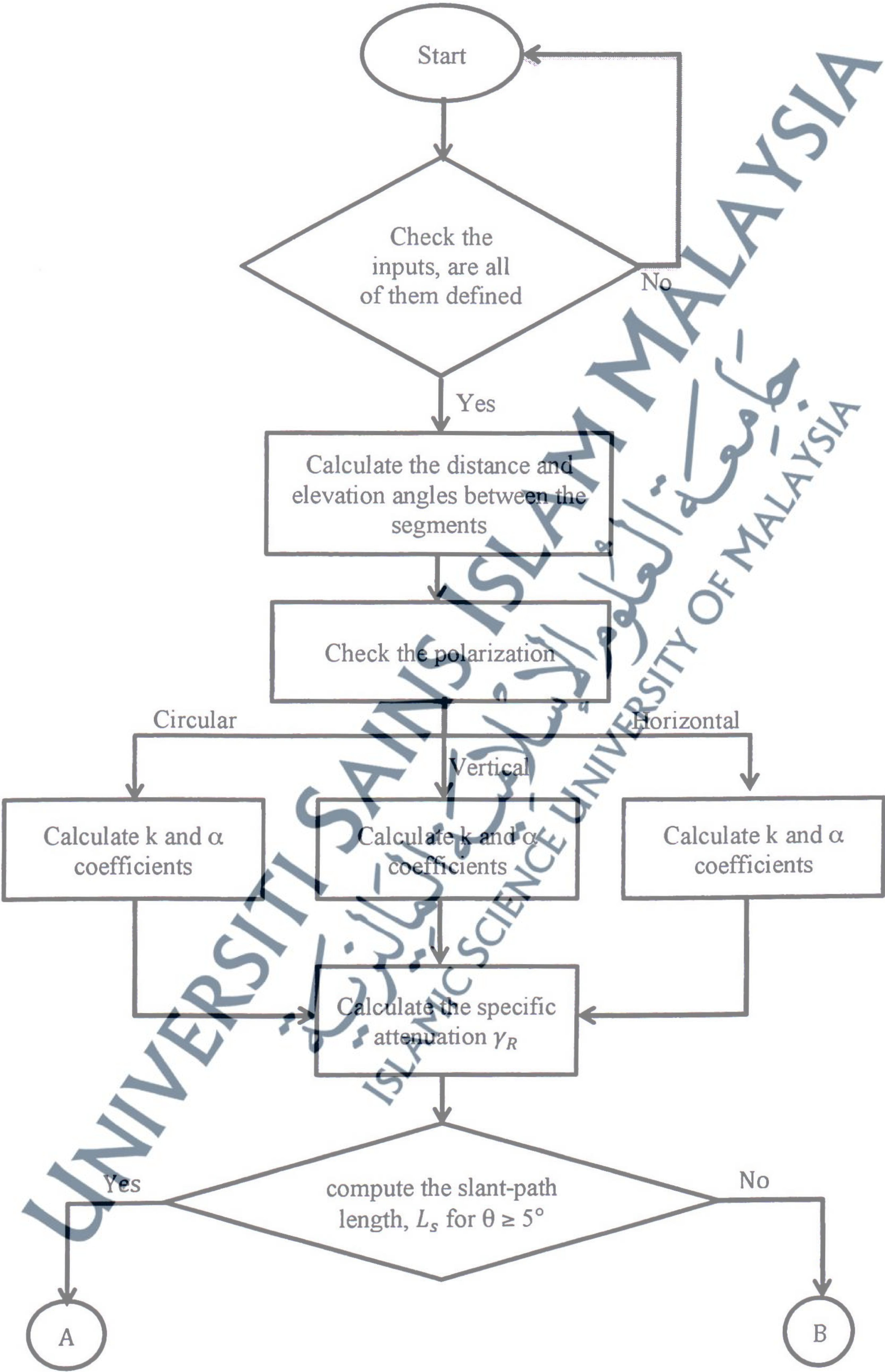
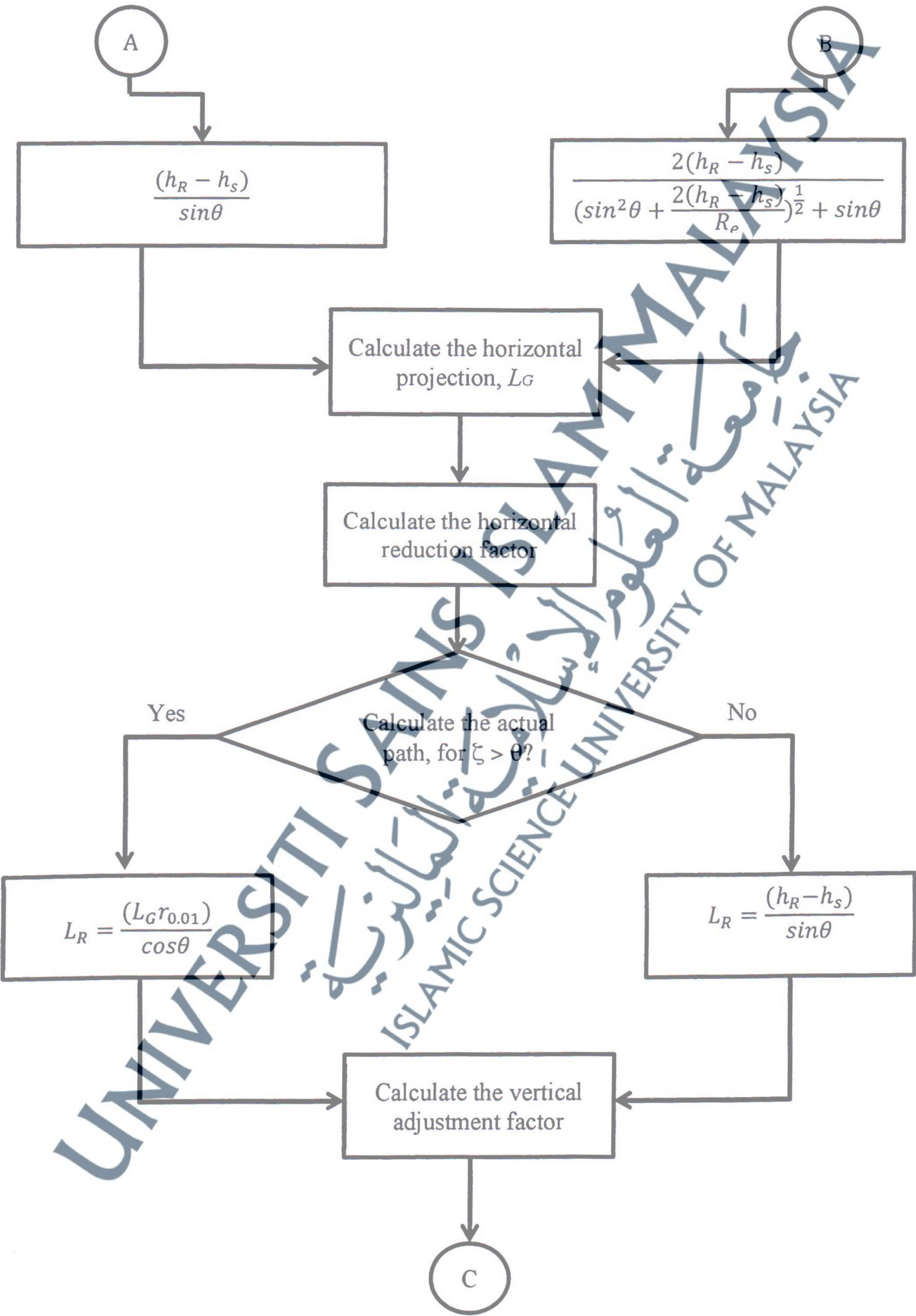
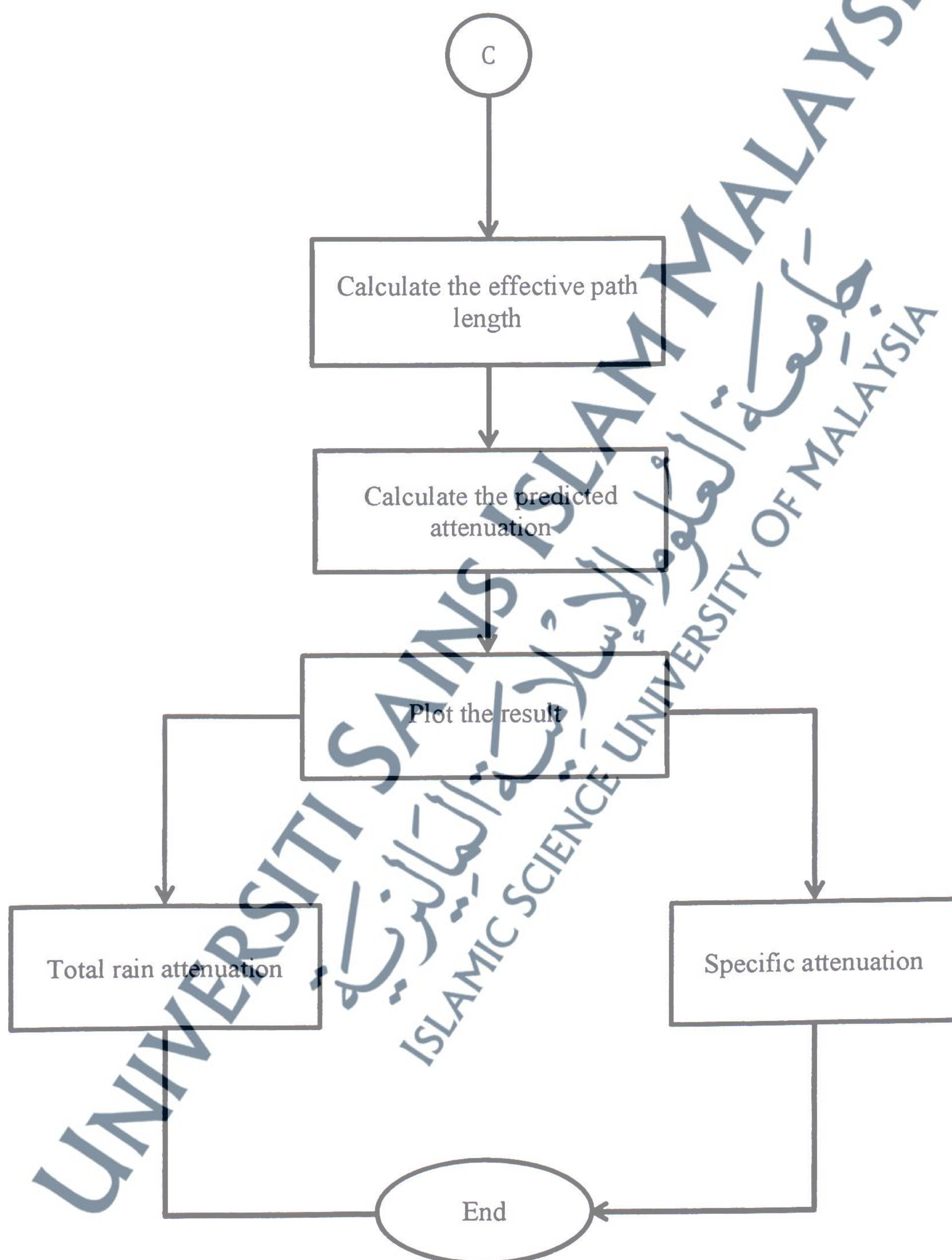




Figure 2.16-B: Flowchart design for ITU-R model





**Figure 2.16-C:** Flowchart design for ITU-R model



### 2.17.3 Rain Microstructure

In the millimeter-wave range of the radio spectrum, the number and the size of the rain particles play a significant role for signal degradation, because the scattering and absorption due to rain is dependent on the drop size distribution (DSD). DSD can be interpreted as the number of raindrops per unit volume. These parameters have to be understood in order to develop and/or evaluate the precipitation prediction models.

The attenuation of rain based on the knowledge of the rain microstructure requires a model that specifies the rain rate and the size distribution of the raindrops.

The path attenuation in decibels of a radio wave of length  $L$  due to rain is found by the following (Ippolito, L. J. 1981)

$$A_{dB} = 4.343 \int_0^L \int_0^\infty Q_t(r, \lambda, m) N_{(D)} dr dl \quad (2.23)$$

where  $N_{(D)}$  is the drop size distribution as a function of the rain rate.  $Q_t$  is the rain attenuation cross-section of a single drop of radius  $r$ , the attenuation cross section is a summation of the absorption and scattering for each drop, where it's function in the wave length, refractive index, as well as drop radius.  $N_{(D)}$  can be defined as the number of drops per unit volume.

#### 2.17.3.1 Raindrop Size Distribution

The raindrop distribution is denoted by  $N_{(D)}$  with units of  $m^{-3}$ , DSD provides one of the most comprehensive representations of the natural raindrop distributions (Matthew, 2000), where  $D$  is the drop radius. Rain can be formed by drops of many different diameters, thus the actual drop size distribution might vary widely in rain storms, but the average distribution is almost stable (CCIR [1981a], 1981). The DSD



for different rain drops size and different rainfall intensities will be examined in this chapter.

### 2.17.3.2 Marshall-Palmer DSD

The raindrop size distribution has been studied by many researchers to evaluate the rain behaviors. The DSD modeling is generally distributed exponentially. The most widely used DSD in scientific literature is the Marshall and Palmer model (Marshall & Palmer, 1948), which is an exponential distribution with two fitting parameters  $N_0$  and  $\Lambda$ . A brief description of the Marshall-Palmer DSD is shown using the following expression:

$$N_{(D)} = N_0 e^{-\Lambda D} \quad [m^{-3}] \quad (2.24)$$

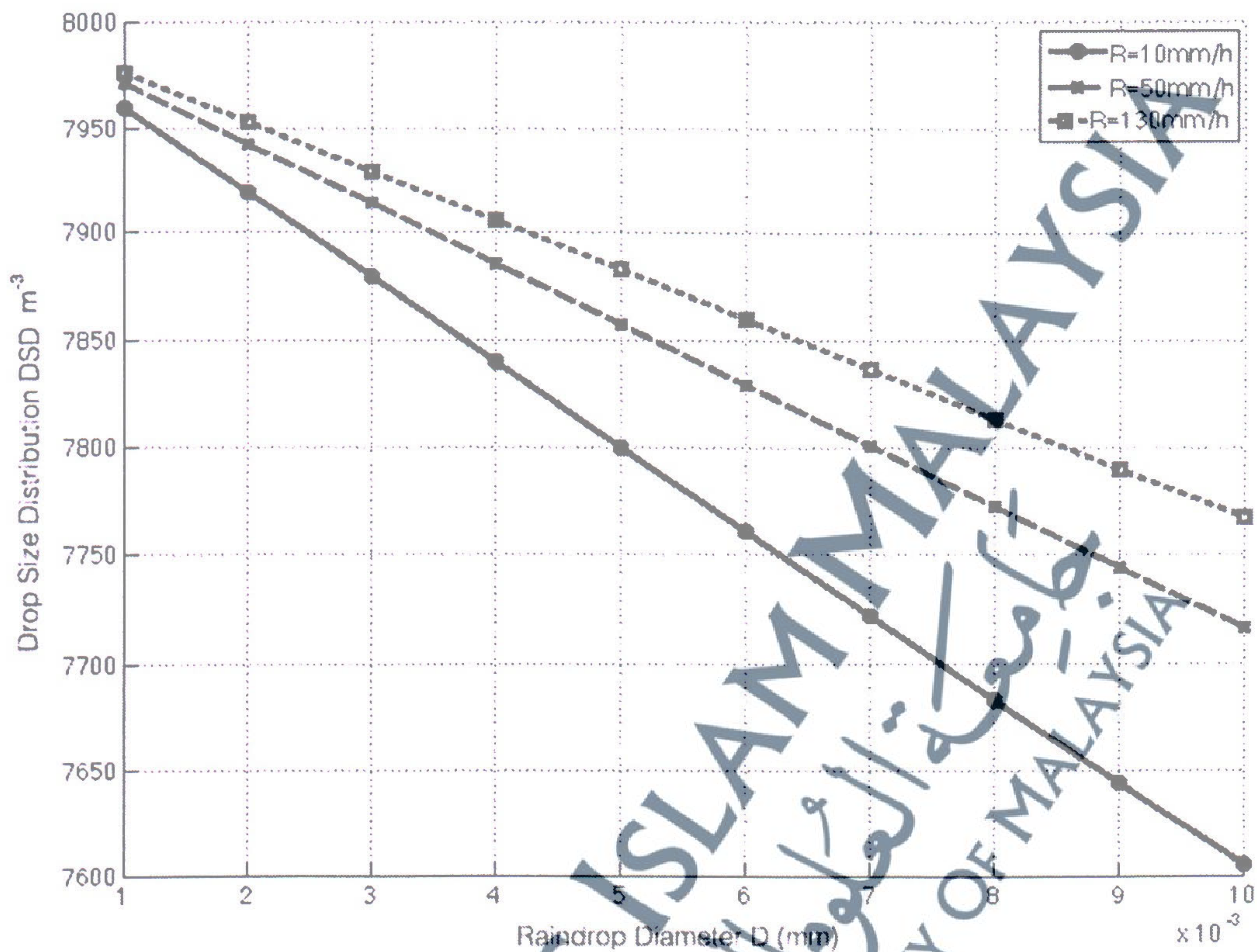
where  $N_{(D)}$  is the number of rain drops per cubic meter  $m^{-3}$ ,  $N_0 = 8 * 10^6$ ,  $D$  is the drop diameter in unit of meters and  $\Lambda$  and  $N_0$  are empirical constants determined from the measured distributions (Vidyarthi et al., 2011).  $\Lambda$  is related to the rain rate  $R$  (mm/hr) as follows

$$\Lambda = 4100 R^{0.21} \quad [m^{-1}] \quad (2.25)$$

Figure 2.17 which calculated using Equation 2.24 shows the representation of the Marshall-Palmer DSD with three different rain rates.



Figure 2.17: Relation Between DSD and Raindrop Diameter for Different Rainfall Rates



It is clearly noted that the drop size distribution decreases as the drop radius increases, while the DSD increases directly when the rain intensity increases.

2.17.3.3 Rain Cross Section

The rain attenuation of a radio wave propagating in a volume of rain of extent  $d$  in the direction of wave propagation can be modeled by integrating the cross-section of rain drops over a complete signal path penetrated in rain and can be expressed as

$$A = \int_0^L \gamma \, dl \quad [dB] \tag{2.26}$$



From the fundamentals of electromagnetic theory, it has been established that the magnitude of an electromagnetic wave traveling through a rain-filled medium in a distance  $L$ , decays in amplitude by a factor of  $e^{-\gamma d}$  where  $\gamma$  is the attenuation coefficient (Testud et al., 2001 and Matthew. 2007), which is given by

$$\gamma = N_0 Q_t \quad (2.27)$$

where  $N_0$  is the number of rain drops per unit volume, and  $Q_t$  is the attenuation cross-section due to the drop of radius  $a$ . The attenuation cross section is a summation of the absorption  $Q_a$  and scattering  $Q_s$  for each drop.

The principle of signal attenuation of radio waves in dB can be written as

$$A_{dB} = 10 \log \frac{1}{e^{-\gamma d}} \quad (2.28)$$

where  $e=2.718$ , therefore the signal attenuation can be written as:

$$A_{dB} = 4.343 \gamma d \quad (2.29)$$

Where  $\gamma$  is the specific attenuation and it can be written as:

$$\gamma = Q_t(r, \lambda, m) N_{(D)} \quad (2.30)$$

In real situations, the raindrops do not all have a uniform radius. Therefore, the attenuation coefficient must be determined by integrating it over all of the drop sizes.

$$\gamma = 4.343 \int Q_t(r, \lambda, m) N_{(D)} dr \quad (2.31)$$



Equation 2.31 shows the dependence of rain attenuation on drop sizes, drop size distribution, rain rate, as well as the drop cross section.

Raindrops cross-section  $Q_t$  is found by applying the Mie scattering theory for a plane wave radiated through an absorbing sphere (Hulst & Van, 1957).

$$Q_t = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1) \text{Re}[a_n + b_n] \quad (2.32)$$

where  $a_n$  and  $b_n$  are Mie scattering coefficients.

Using Equation 2.24 and Equation 2.32, the rain specific attenuation in dB/km can be expressed by

$$\gamma = 4.343 \int_0^{\infty} Q_t(r, \lambda, m) N_{(D)} dr \quad (2.33)$$

where  $Q_t$  is the attenuation cross section of the rain drop which can be obtained from Equation 2.32. The integration in Equation 2.33 can be calculated numerically for specified values of drop size distribution and raindrop cross section.

#### 2.17.4 Summary

This chapter started with a background of the rain attenuation studies and the modeling of the rain attenuation over the earth-to-space links. The basic concepts of rainfall characteristics, rain structure, and the rainfall distribution, including Malaysian climate are discussed. Global rainfall types, scattering and absorption due to rain, rain attenuation modeling are also presented.

The, chapter also discusses the concept for HAPS system fundamentals and architecture, frequency spectrum, HAPS area coverage and Malaysia activities on HAPS.



The fundamentals of satellite communication systems, HAPS network, and HAPS-to-Satellite integration are also discussed in this chapter.

The chapter is also discusses the modeling of rain attenuation over the slant path links. The ITU-R world wide model for specific attenuation, rain height, and effective bath length along horizontal reduction and vertical adjustment factors also presented.

