TERAHERTZ COMMUNICATION FOR SATELLITE NETWORKS

by

Pulkit Hanswal

June 1, 2018

A thesis submitted to the
Faculty of the Graduate School of
the University at Buffalo, State University of New York
in partial fulfillment of the requirements for the
degree of

Master of Science

Department of Electrical Engineering
Acknowledgements

I would like to express my sincere gratitude to my advisor Dr. Josep M. Jornet for the continuous support during my Master thesis and related research, for his patience, motivation and immense knowledge. The door to Dr. Josep M. Jornet office was always open whenever I ran into a trouble spot or had a question about my research or writing. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Master thesis.

Besides my advisor, I would like to thank Dr. Elena Bernal Mor for her encouragement, advise throughout my years of study and recommending me for the Master thesis to Dr. Josep M. Jornet.

Finally, I must express my profound gratitude to my parents for providing me with unfailing support and continuous encouragement. This accomplishment would not have been possible without them.
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Abstract

Satellite communication, no longer a marvel of human space activity, has become a fact of everyday life. Satellites are used extensively for a variety of communication applications. In recent years, there is growing interest in the field of satellite networks which enables a whole new class of missions for navigation, communication and remote sensing. Consequently, there is a need for innovative methodologies to meet the increasing demand for high-speed wireless communication. Terahertz band communication is envisioned to be the key technology to satisfy the need for high data rates. Due to the large availability of bandwidth at terahertz band, wireless terabit per second links are expected to become reality very soon.

The objective of this work is to study the feasibility of using terahertz band for inter-satellite communication. We have developed a propagation model considering several impairments which can affect the propagation of terahertz wave in inter-satellite links. We have also analyzed noise sources which can impact the terahertz-based communication and calculated the effective noise temperature at the satellite antenna. A link budget analysis to calculate the gain of the antenna required to maintain the quality of the link is conducted and a comparative analysis of terahertz-based and optical-based inter-satellite communication on the basis of pointing requirements is also done. Lastly, we have addressed some of the additional challenges that we need to overcome for implementing terahertz-based inter-satellite communication.
A satellite is a body that moves around another body (usually much larger) in a mathematically predictable path called an orbit. Satellites orbiting around earth can revolve either in circular or elliptical path. Satellites are used for many purposes. Common types include Earth observation satellites, navigation satellites, communication satellites, weather satellites, and space telescopes. We mainly focus in this text on communication satellites.

1.1 Basic Characteristics of Satellites

A communication satellite is a repeater satellite orbiting around earth which enables multiple users with appropriate earth stations to deliver or exchange information. Two earth stations which are very distant geographically can make use of communication satellite which can relay and amplify the signals via a transponder. The source earth station sends a transmission to the satellite. This is called up-link communication. The satellite transponder then amplifies or relays the signal and send it down to the destination earth station. This is called the
down-link communication.

Figure 1.1: Elements of the space segment

1.1.1 System Elements

A communication satellite system can be divided into two major parts, the space segment and the ground segment.

Space Segment

The space segment includes the satellite, the launch station and tracking, telemetry and command (TT&C) station. Figure 1.1 depicts the main elements of the space segment. Deployment of a satellite in an orbit is accomplished by the help of a spacecraft manufacturer and launch agency. After the satellite is placed in the proper orbit, it is vital to monitor the satellite for the duration of its mission. This task is accomplished by TT&C station (or stations). The TT&C station establishes a monitor link to provide essential management and control functions for the safe
operation of the satellite. The link between the satellite and TT&C station is usually separate from the link used for user communication. Tracking, telemetry and control station is specialized earth terminal facility specifically designed for the complex operation required to maintain a satellite in orbit.

**Ground Segment**

The ground segment of the communication satellite system consists of earth stations that utilize the communication capabilities of space segment. The earth stations communicate with satellites to meet the communication needs of the user. It is important to note that the term earth station is an accepted term that include the communication stations on the ground, in the air (on airplanes), or on the sea (on ships). Figure 1.2 depicts a typical ground segment; a single satellite is shown which acts as a relay to establish the links from one earth station to another.

![Figure 1.2: Ground segment](image)

It is important to note that depending upon the coverage area of a satellite,
there can be satellite to satellite link in a satellite system. Figure 1.3 depicts Inter-satellite links (ISL) and Ground-satellite links (GSL).

Figure 1.3: Satellite Links

1.1.2 Types of Satellite Services

Satellite services are broadly categorized into

- Fixed-satellite service (FSS) - This is a type of radio communication service between earth stations at specific fixed positions. There are many subdivisions within FSS, e.g., the FSS provide links for telephone networks as well as for transmitting TV signals to cable companies. Figure 1.4 depicts a typical example of fixed satellite service.
1.1. Basic Characteristics of Satellites

- Broadcast-satellite service (BSS) - In this service, the signal transmitted by the satellite is intended mainly for direct broadcast to the home. It is sometimes referred to as direct broadcast satellite (DBS) service. One of the most common example of BSS is Direct to Home (DTH) television. As shown in Figure 1.5, satellite is broadcasting signal to all the users within the satellite coverage.

- Mobile-satellite service (MSS) - In this type of service there is communication between mobile earth stations with the help of one or more satellites. MSS would include land mobile, maritime mobile, and aeronautical mobile. Figure
1.1. Basic Characteristics of Satellites

Figure 1.6: Mobile satellite service

- Navigation satellite service (NSS) - A navigation satellite service uses a network of satellites (typically 18-30 satellites for global coverage) for providing geo-spatial positioning. An NSS with global coverage is termed as global navigation satellite system (GNSS). The most famous example of NSS is United States’ Global Positioning System (GPS). Figure 1.7 illustrates a GPS constellation.
### 1.1.3 Benefits of Satellite Communication

The use of the satellites for communication has become a fact of everyday life. Satellites are used extensively for a variety of communication applications. It is evidenced by many homes which are equipped with dishes used for the reception of satellite television. Satellites also form an essential part of telecommunications systems worldwide, carrying large amounts of data and voice traffic. As mentioned in [2], some of the advantages of using satellites are as follows:

1) **Wide Coverage Area (Country, Continent or Globe)** - When designed properly, a satellite can serve region of any size that can see it. However, in terrestrial systems, the coverage area is limited usually within a country.

2) **Independence from Terrestrial Infrastructure** - By providing wide coverage area and acting as repeater station in space, satellite aids in reducing the terrestrial
infrastructure. Two earth station far distant geographically can communicate without any external connections using satellite (or satellites). It becomes really attractive in remote areas where the terrestrial infrastructure is poor.

3) Uniform Service Characteristics - Footprint of the satellite defines the service area of the satellite. As we will discuss later in this chapter, footprint depends upon the altitude of the satellite. Within the footprint of the satellite, services are delivered in precisely the same form. However, in terrestrial systems the quality of the received signal depend upon the location, e.g., remote areas with poor terrestrial infrastructure does not have good quality of received signal.

4) Wide Bandwidth Availability- The bandwidth allocated for the satellite services is generally high. As a result, satellite users enjoy ample amount of bandwidth. Since, there is a direct relationship between bandwidth and data rate. An increase in bandwidth can enhance the speed of communication.

5) Rapid Installation & Low Cost - As mentioned in [2], once the satellite system is operational, the earth station in the ground segment can be installed very quickly. This is because unlike terrestrial system it does not require extensive planning such as laying down cables and towers throughout the area. Furthermore, the cost of constructing a single site is quite modest.

### 1.1.4 Frequency Spectrum Allocations

Frequency allocation to satellite services is a complicated process which requires planning and coordination. Frequency band allocation is done by the International Telecommunication Union (ITU), a specialized agency of the United Nations. Table 1.1 lists the frequency bands assigned by ITU for satellite services.
### Table 1.1: Frequency band allocations

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</tr>
<tr>
<td>S</td>
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</tr>
<tr>
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<td>X</td>
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<td>FSS, Earth observation, Meteorological satellite service</td>
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<td>Ku</td>
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<td>FSS, BSS</td>
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<tr>
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<td>18-20 GHz DL; 27-31 GHz UL</td>
<td>FSS, BSS</td>
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<td>V</td>
<td>60 GHz DL; 50 GHz UL</td>
<td>Open band</td>
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### 1.2 Satellite Classification

There are many ways to classify satellites. Some of them include inclination classification, synchronous classification, altitude classification.

a) Inclination classification - This divides satellites on the basis of inclination with reference to the equatorial earth plane. Figure 1.8 illustrates the types of satellites based on inclination classification.

![Figure 1.8: Inclination classification](image)

b) Synchronous classification - In this type of classification, satellites are divided on the basis of the synchronization between the orbital period and rotational period of the earth. A geosynchronous orbit (GSO) satellite has an orbital period equal to the rotational period of the earth. Geosynchronous orbit (GSO) satellites rotate
around the earth at an altitude of 35,786 km. The synchronization of the rotational and orbital period means that the satellite return to the same position in the sky after a period of one day. The path of the satellite over the course of one day depends upon the inclination and eccentricity of the GSO.

c) Altitude classification - This divides satellites by their altitude from the earth. Figure 1.9 provides three classical Earth-orbit schemes. The commonly used altitude classifications are Geostationary earth orbit (GEO) satellites, Medium earth orbit (MEO) satellites and Low earth orbit (LEO) satellites. We mainly focus in this text on the classification based on altitude.

![LEO, MEO, and GEO orbits](image)

Figure 1.9: LEO, MEO, and GEO. Only one orbit per altitude is illustrated, even though LEO and MEO satellites require multiple orbits for continuous service.

### 1.2.1 GEO Satellites

Geostationary earth orbit is a special case of GSO, which is circular and inclined at 0° to Earth's equatorial plane. Satellites in GEO revolve at an altitude of about 35,786 km. A satellite in a GEO appears always at the the same point in sky to the observers on the surface. They are mainly used for FSS, BSS and meteorological satellite service.
Chapter 1. Introduction  1.2. Satellite Classification

Figure 1.10: GEO satellite system

Advantages

1. Due to very high altitude, GEO satellites have very large coverage area. It requires only 3 satellites to cover every part of earth. Figure 1.10 shows a system of three geostationary communication satellites.

2. As GEO satellites have 24 hour view of a particular location, they are highly desirable for services which require fixed antenna positions, e.g., DTH, TV and radio broadcasting

3. As the coverage area of GEO satellites is very wide, there is no need of handing over the signal from one satellite to another.

4. The Doppler spread in communication between satellite and earth station is minimal as there is no relative motion between them.

Disadvantages

1. Due to large distance from earth, there is a very high latency which makes it unfit for voice and data communications.

2. Due to large footprints we cannot reuse frequency.

3. As we will see in the later chapters, more distance leads to high propagation loss which eventually leads to poor quality of signal at the receiver.

4. In order to maintain the quality of the link, high transmit power is needed
which is a problem for battery powered devices.

1.2.2 LEO Satellites

LEO satellites revolves in geocentric (around earth) orbits ranging in altitude from 180 km – 2000 km (1,200 mi). LEO satellites do not stay in fixed position relative to the surface, and are only visible for 15 to 20 minutes each pass. They have rotation period of 90 to 120 minutes, with speed 20000 to 25000 km/h. They are mainly used for FSS and MSS.

Advantages

1. Due to it’s proximity to earth compared to GEO satellite, there is better signal strength in comparison to GEO satellites.
2. They need lesser transmit power for communication in comparison to GEO satellites.
3. There is very low latency of around 10 milliseconds.
4. They have smaller footprints so there can be frequency reuse.

Disadvantages

1. A network of LEO satellites (50-200), which is also known as satellite constellation, is required to cover entire earth because of the small footprint. There are satellite to satellite links in the case of LEO satellite network for handing over the information.
2. The lifetime of LEO satellite is shorter than GEO satellites (5-8 years). This is because of the atmospheric drag which causes gradual orbital deterioration.
3. There is Doppler spread in the communication between LEO satellite and earth station because of the relative motion between them.
4. There is need for routing from satellite to satellite to base stations for global
Chapter 1. Introduction  1.2. Satellite Classification

coverage.

5. There is requirement for a mechanism for correct handover of the signal from one satellite to another.

Some of the examples of LEO satellite systems are as follows

- Iridium system - It has 66 satellite in 6 LEO orbits which is used to provide direct worldwide communication, i.e., voice, data paging, fax. Figure 1.11 illustrates an iridium satellite constellation.

- Teledesic - It provides fiber-optic like (broadband channels, low error rate, and low delay) communication. It has 288 satellites in 12 LEO polar orbits.

1.2.3 MEO Satellites

MEO satellites revolves in geocentric orbits ranging in altitude from 2000 km – 35,786 km. MEO satellites are visible for much longer periods of time than LEO satellites, usually between 2 – 8 hours. They are used mainly for NSS.
Advantages

1. A MEO satellites’ wider footprint and slower movement in comparison to LEO satellite means fewer satellites are needed in MEO network than in LEO network. MEO satellite networks also make use of satellite to satellite links.
2. Shorter time delay and stronger signal than GEO satellite.
3. It requires fewer handover than LEO network.

Disadvantages

1. Delay is about 70-80 milliseconds.
2. Needs higher transmit power than LEO satellites.

A well known example of MEO satellite network is GPS.

- GPS comprises of 24 satellites in six orbits. They are used for land, sea and air navigation to provide time and locations for vehicles and ships. The satellites are placed in orbit in such a way that minimum four satellites are visible from any point on the earth.

1.3 Inter-Satellite Communication

Inter-satellite communication is mainly used for providing global coverage with the help of satellite to satellite links. There are two types of ISL, intra-orbital links and inter-orbital links. Intra-orbital links connects the satellites on the same orbit while inter-orbital links connects the satellites on different orbits. Inter-satellite communication becomes a necessity in the case of LEO and MEO satellite networks because of their smaller footprint and the need for global coverage. Apart from LEO and MEO satellite networks, they can also be used for communication between GEO satellite and LEO satellite. An example of such a satellite system is Tracking
and Data Relay Satellite system (TDRS). There are 9 Tracking and Data Relay satellites which sit at about 35,400 km (almost GEO) above the earth. Occasionally, satellites present in the LEO orbit are unable to pass along their information to Earth in the case of unclear view of the ground station. In such a case, TDRS serves as a way to pass along the satellite information. Figure 1.12 illustrates a TDRS system. Some of the other well known examples of satellite constellations which make use of ISL are Iridium and Teledesic. Apart from providing global coverage, ISL helps considerably in reducing the terrestrial infrastructure. This is because we need only 1 up-link and 1 down-link per direction for any point to point communication.

1.3.1 ISL Frequency Bands

Currently, there are two types of ISL based upon the technology used for communication between satellites. Radio Frequency (RF) based ISL make use of microwaves (0.3 GHz-30 GHz) and millimeter waves (30 GHz - 300 GHz) while
optical communication based ISL make use of visible spectrum, i.e., wavelength range of about 390 nm to 700 nm, for communication.

**Radio Frequency based ISL**

Long term experience with radio equipment developed for space to ground links makes RF based ISL more easier to implement in space. As described in [7], in comparison to optical based ISL, RF based ISL appears more reliable. However, due to less availability of bandwidth the data rate achievable in RF link is lower than the optical link. As we will see in the later chapters, due to low carrier frequency RF links can provide omni directional coverage and also has higher beam width than optical links which reduces the need for highly accurate acquisition, tracking and pointing (ATP) subsystem. Although, this high beam width makes RF links subjected to interference and multi path propagation. Figure 1.13 illustrates an iridium satellite system which makes use of RF based ISL.

![Figure 1.13: RF based ISL](image)

Table 1.2 indicates the frequency bands allocated to RF based ISL by radio communication regulations. As we will see in chapter 2, these allocations have been done because of the strong molecular absorption by the atmosphere at these
frequencies. Using these frequencies for ISL provide protection against interference between terrestrial system and satellite network.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>22.55 GHz - 23.55 GHz</td>
</tr>
<tr>
<td></td>
<td>24.45 GHz - 24.75 GHz</td>
</tr>
<tr>
<td></td>
<td>32 GHz - 33 GHz</td>
</tr>
<tr>
<td>V</td>
<td>59 GHz - 64 GHz</td>
</tr>
<tr>
<td></td>
<td>65 GHz - 71 GHz</td>
</tr>
</tbody>
</table>

Table 1.2: Frequency bands for RF based ISL

**Optical Communication based ISL**

Optical communication based ISL has the advantage of providing high speed communication with the data rate of the order of gigabits per second (Gbps). However, due to high carrier frequency they have very low beam width. As mentioned in [10], the challenging part in using optical communication for ISL is the requirement of an highly accurate ATP subsystem for establishing and maintaining the communication link. In order to maintain a link in optical communication based ISL, a direct line of sight is required between transmitter and receiver. The process of maintaining the link becomes even more complex due to the rapid relative motion between two satellites. Although, the low beam width of the optical based ISL aids in receiving interference free signal and also reduces the possibility of interception. They can also be used for communication between spacecrafts when they reach very short distances with respect to each other which guarantees very high position accuracy. A well known example of the optical based ISL is the TDRS system which makes use of laser for communication.
1.4 Terahertz Based ISL

1.4.1 Terahertz Communication

Terahertz band (0.1 THz-10 THz) communication is considered to be the key technology to support the increasing demand for high speed wireless communication in the recent years. Due to the large availability of bandwidth at THz band, wireless terabit per second (Tbps) links are expected to become reality very soon. As we will see in the next chapter, this very large bandwidth comes at the cost of a very high propagation loss. The high propagation loss is primarily due to the high molecular absorption at THz frequencies and also due to the increase in spreading loss at higher frequency. The advancements in the field of communication can compensate for the propagation loss at higher frequencies but the high molecular absorption remains an issue. Consequently, for the time being, THz band communication in terrestrial environment is mainly constrained to very short (e.g., on chip) and short (e.g., in a room) links.
In this work, we propose satellite to satellite links using THz frequencies. Due to the high availability of bandwidth, THz based ISL can enable higher data rate in comparison to RF based ISL without having to switch to a different set of hardware such as lasers for optical communication. Also, due to the high frequency of the communication system, the size of the antenna required for THz based ISL is very less which is highly favorable to the smaller satellite systems. Terahertz spectrum also provides inherent isolation from terrestrial RF systems and thus eliminates potential radio frequency interference from ground systems. Furthermore, as explained in [7], because of the presence of multiple GHz channel bandwidth terahertz wireless system has very low complexity system design with simplest modulation schemes in comparison to traditional radio architectures. As we will show in the future chapters, THz based inter-satellite communication also have higher efficiency than optical communication based ISL.

1.4.2 Summary of Contributions

In the following chapters, we will develop a propagation model and learn about the factors affecting the THz wave propagation in ISL. In Chapter 3, we will look into the noise sources which can affect THz based inter-satellite communication. In Chapter 4, we will conduct a link budget analysis and do a comparative study between optical and terahertz based ISL. Finally, we will address some of the major challenges that we need to overcome for implementing THz based inter-satellite communication.
CHAPTER 2

Terahertz Wave Propagation in ISL

When a THz wave propagates through a medium there can be several impairments. Some of the important impairments which affect THz wave propagation will be described in this chapter.

2.1 Spreading Loss

Spreading loss indicates the amount of power that is lost when an EM wave propagates in an environment. Once THz wave is several dimensions away from its emitter, its energy propagates out radially. Figure 2.1 depicts THz wave propagation from an elemental antenna.
Consider an isotropic point source with a transmitting power of $P_t$. At a
distance $d$ from the source, the radiated power is uniformly distributed over the
surface area of a sphere.
We can write the received power $P_r$ at distance $d$ is given by

$$P_r = P_t G_t \frac{1}{4\pi d^2} A_e,$$  \hspace{1cm} (2.1)

where $G_t$ is gain of the transmitter antenna and $A_e$ is the effective aperture of the
receiver antenna. We can also write the gain of the receiver antenna $G_r$ by

$$G_r = \frac{4\pi}{\lambda^2} A_e,$$  \hspace{1cm} (2.2)

where $\lambda$ is the wavelength of the THz wave.
After substitution we get,

$$P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2,$$  \hspace{1cm} (2.3)

which we can further rewrite to

$$P_r = P_t G_t G_r \left( \frac{c}{4\pi df} \right)^2,$$  \hspace{1cm} (2.4)
where \( c \) is the speed at which THz wave propagates in a medium & \( f_c \) is the carrier frequency of the wave. The spreading loss is given by

\[
L = \frac{1}{G_t G_r} \left( \frac{4\pi df_c}{c} \right)^2. \tag{2.5}
\]

We can further express this equation in decibels (dB).

\[
P_{r_{dB}} = P_{t_{dB}} + G_{t_{dB}} + G_{r_{dB}} - L_{dB}. \tag{2.6}
\]

The propagation model described by equation (2.6) is known as Friis propagation model. From equation (2.5), we can see that as we increase the carrier frequency the power received at the receiver antenna decreases. This equation explains the cause of high spreading loss, when communicating at THz frequencies. We can also see that this spreading loss can be compensated by increasing the gain of the receiver and transmitter antennas. The propagation loss also increases as we increase the distance between transmitter and receiver. The propagation model described above is also known as free-space model. This model very well fits our scenario. We will be using this model to conduct link-budget analysis in the Chapter 4.

### 2.2 Absorption Loss

Atmospheric absorption of electromagnetic radiation happens when the energy of the photon present in the radiation is taken by the molecules (typically electrons of atom) in the atmosphere. This electromagnetic energy absorbed by the molecules is usually converted into another form such as thermal energy. Figure 2.2 illustrates the wavelengths at which the EM waves are not able to penetrate the Earth’s atmosphere. The primary gases which leads to atmospheric absorption of energy are water vapor, ozone and carbon dioxide. As shown in Figure 2.2, the wavelengths
in the range of 30 \( \mu m \) to 3000 \( \mu m \) (Terahertz range) are completely absorbed by Earth’s atmosphere. This absorption is mainly due to the water vapor present in the atmosphere.

![Diagram of atmospheric windows](image)

**Figure 2.2:** Diagram of atmospheric windows

Figure 2.3 shows attenuation due to water vapor in the range of 0.1 THz to 10 THz. It shows that the attenuation can go as high as 1000 dB for some specific frequencies. Due to this very strong absorption we are unable to use THz frequencies for terrestrial systems.
Chapter 2. Terahertz Wave Propagation in ISL

2.2. Absorption Loss

Figure 2.3: Absorption loss at THz frequency due to water vapor in dB/km

Layers of Earth’s Atmosphere

In order to analyze the impact of atmospheric absorption on THz based ISL, we should first study about the layers of atmosphere. Earth’s atmosphere consists of series of layers each of which has its own properties. Moving upward from the ground level, these layer are named as troposphere, stratosphere, mesosphere, thermosphere and exosphere. Figure 2.4 depicts all the layers of atmosphere.

- Troposphere - The troposphere is the lowest layer of the atmosphere. It extends upward from ground level to about 10 km (33,000 feet) above sea level. 99% of the water vapor in the atmosphere is found in the troposphere. As we move up in the troposphere temperature gets colder.

- Stratosphere - The stratosphere extends from the top of troposphere to about 50 km above the ground. This layer contains the ozone molecules which absorb the high-energy ultraviolet (UV) light from the Sun, which is then converted into thermal energy. The temperature of the stratosphere gets
warmer as we move upwards.

- **Mesosphere** - The next layer up is called mesosphere. It extends upward to a height of about 85 km above earth. Unlike the stratosphere, temperature once again grows colder as we rise up through the mesosphere. The top of the mesosphere is the coldest place in earth’s atmosphere with a temperature around -85°C (188°K). The air density in mesosphere is far too low to breathe. Also, the air pressure at the bottom of the mesosphere is 1% of the pressure at sea level.

- **Thermosphere** - Above the mesosphere is the thermosphere. As mentioned in [11], this layer is completely free of water vapor. High energy X-rays and UV radiation from the Sun are absorbed in the thermosphere. As a result, temperature of the thermosphere can range from about 500°C (773°K) to 2000°C (2273°K). However, as we will see in the next chapter, due to very low density of the air the notion of the temperature is not meaningful at this layer. The top of the thermosphere lies between 500 to 1000 km depending upon the amount of the radiation coming from the sun. LEO and many MEO satellites orbit at this layer.

- **Exosphere** - The exosphere is the topmost layer of the atmosphere. The air is very, very thin at this layer of the atmosphere. The top of the exosphere lies at about 10000 km after which it finally fades into space. This layer is also completely free of water vapor.
As mentioned above, layers thermosphere and exosphere of the atmosphere does not contain any amount of water vapor. Figure 2.3 shows the impact of water vapor on THz frequencies. Since LEO & MEO satellites are present at the thermosphere and exosphere layer of the atmosphere while GEO satellites are present in deep space, we can say that in THz based ISL the absorption of the THz frequencies will be negligible. Thus, absorption will not have a considerable affect on THz based ISL.

2.3 Scattering Loss

Scattering is a process in which some forms of radiation, such as light, change its path from straight trajectory into one or more paths. Scattering occurs due to the deformities present in the material medium through which the EM wave pass.

It is important to understand that reflection, refraction and scattering all leads
to the re-direction of light. When the medium is uniform and homogeneous over lengths that are much larger than the wavelength then a well-defined direction of propagation emerges. This is refraction. However, when the medium is smaller or comparable to the wavelength then the wave goes off in different direction. This is scattering. We can say that refraction is a form a scattering. Scattering of the electromagnetic waves corresponds to the collision and scattering of a wave with some material object.

**Types of Scattering**

Depending upon the size of the material object with which the EM wave colloids, scattering can be categorized into three.

- **Rayleigh Scattering** – This occurs when the size of particle is small in comparison to the wavelength of the wave.

- **Mie Scattering** – This type of scattering occurs when particle is about the same size as wavelength of the wave

- **Geometric Scattering** – This is caused when the particle is much larger than the wavelength of wave

In order to do the analysis of the impact of scattering on THz Based Inter-satellite communication, we should first analyze the type of scattering which occurs at the layers where satellites are present.

In case of optical/laser communication geometric scattering is mainly caused by rain droplets and snow [15]. Aerosol particles, fog and haze are major contributors of mie scattering [14] while rayleigh scattering is mainly caused by air molecules [16].

As we discussed above, in thermosphere and exosphere the only thing which is present is air molecules with very low density. Now, in our scenario we are transmitting at THz frequency which means at higher wavelength than the wavelength
used in optical communication. So, we can infer that only scattering which is possible in THz based ISL is rayleigh scattering.

In the case of rayleigh scattering the relation between amount of scattering and wavelength is given by \[ I \propto \frac{1}{\lambda^4}, \quad (2.7) \]

where \( \lambda \) is the wavelength of the THz wave and \( I \) is the intensity of the light scattered.

As described in [12], rayleigh scattering is neglected at wavelengths in the near infrared range (0.75 \( \mu \)m-1.4 \( \mu \)m). In THz based ISL, we are transmitting at wavelengths higher than the wavelength in the near infrared range. Due to the inverse relationship shown in equation \[ (2.7) \], the impact of scattering in THz based ISL is even lesser in comparison to the scattering in near infrared range. Furthermore, the density of the air molecules in the upper layers of the atmosphere is very less. Thus, we can conclude that when we are using terahertz band for inter satellite communication there cannot be huge impact on the signal quality due to scattering.

### 2.4 Fading Loss

There are mainly three mechanisms through which an EM wave propagate in a terrestrial wireless medium; reflection, which is a type of geometric scattering, diffraction and rayleigh scattering. These mechanisms lead to arrival of multiple electromagnetic waves at the receiver at the same time. These waves usually arrive at receiver from different directions and experience different delay due to traversing unequal distances. The received signal amplitude and phase of each of the wave can differ as they travel different distances. As a result, these EM waves can add
either constructively or destructively. Due to this, we can observe fluctuations in the received signal power. Furthermore, the received signal can vary rapidly in phase and amplitude if there is relative motion between the transmitter and receiver.

When an EM wave propagates from transmitter to receiver, signal suffers one or more reflections. This leads to multi path propagation. Due to unequal distances, time of arrival of each path at the receiver is different. This leads to spreading out of the signal in time. This spread is called as delay spread. As we will discuss in the future chapter, high delay spread can lead to inter symbol interference.

Fading also occurs when there is relative motion between transmitter and receiver. Due to doppler effect, relative motion leads to generation of new frequencies at the receiver. In chapter 5, we will see that high speed of the transmitter or receiver can lead to very rapid change in the channel response causing distortion in the received signal.
Noise is an unwanted disturbance that gets added during the capturing or processing of the desired signal. In this chapter we will mainly look at the type of noise in free space and analyze their impact on THz based inter satellite communication.

3.1 Thermal Noise

Thermal noise is the electronic noise generated by the motion of the charged particles such as electrons inside an electrical conductor. Except at absolute zero temperature, the electrons in every conductor (resistor) are always in thermal motion. This noise is generated even when there is no voltage applied to the conductor. This motion leads to voltage difference between the resistor's terminal. As shown in Figure 3.1, this can be modeled as resistor with the noise source.
3.2 Transceiver Noise Sources

As mentioned in [2], if this resistor is connected to a matched load the thermal noise delivered by the noise source will be equal to

\[ P_n = KTB, \]  \hfill (3.1)

where \( K \) is the Boltzmann constant in Joules per Kelvin \( (K = 1.38 \times 10^{-23} \text{ J/ K}) \), \( T \) is temperature in Kelvin and \( B \) denotes bandwidth in Hz.

We can use equation (3.1) to define an effective noise temperature for the other noise sources too, even if the origin of the noise is not thermal. Any noise source having a noise temperature of \( T_n \) will generate thermal noise equal to a resistor at temperature \( T_n \). It is very important to note that, unlike resistors noise temperature of any noise source is not always equal to its physical temperature.

### 3.2.1 Amplifier Noise Temperature

As discussed in Sec.3.1, we can define effective noise temperature for any type of noise source. Consider a non ideal low noise amplifier (LNA) with gain \( G \). As
shown in Figure 3.2, this amplifier has input signal $S_{in}$ with some noise $N_{in}$. Apart from $N_{in}$, this amplifier will add some extra noise to the signal. As described in Sec.3.1, in a similar way this amplifier can be replaced by an ideal amplifier and an artificial noise source $N_{ai}$.

![Figure 3.2: Non ideal LNA & its equivalent scheme](image)

**Noise Factor**

The noise factor is defined as the signal-to-noise ratio between input and output of the system. The noise factor of the LNA described in Figure 3.2 can be given by

$$F = \frac{SNR_{in}}{SNR_{out}} = 1 + \frac{N_{ai}}{N_{in}} \tag{3.2}$$

In order to make it possible to compare different amplifiers, noise figure is calculated by keeping a reference temperature of 290 K. This artificial noise can now be thought of as fixed. At a temperature of 290K, the value of the noise power per unit hertz can be given by

$$N_0 = kT_0 = 1.38 \times 10^{-23} \times 290 = 4 \times 10^{-23} \text{W/Hz}. \tag{3.3}$$

The noise figure is simply $F$ expressed in decibel

$$Noise Figure = 10 \log_{10} F. \tag{3.4}$$
Noise Temperature

As we can see from equation (3.3) the value of noise power is very low. Sometimes it becomes difficult to deal with these small values. We can rewrite equation (3.2) to

\[ F = 1 + \frac{T_{ai}}{T_0}, \]

(3.5)

which can be further rewritten to

\[ T_{ai} = (F - 1)T_0 = (F - 1) \times 290, \]

(3.6)

where \( T_{ai} \) denotes the effective temperature noise of the LNA, \( T_0 \) is the reference temperature (290K) and \( F \) is the noise figure.

3.2.2 Amplifiers in Cascade

It is possible to calculate the effective noise temperature of the amplifier connected in cascade. The cascade connection is shown in Figure 3.3. The overall gain is

\[ G = G_1G_2. \]

(3.7)
System noise temperature in this case can be given by

\[ T_s = T_{e1} + \frac{T_{e2}}{G_1}, \]  

(3.8)

where \( T_s \) is the system noise temperature, \( T_{e1} \) is the noise temperature of the first amplifier, \( G_1 \) is the gain of the first amplifier and \( T_{e2} \) is the noise temperature of the second amplifier. Using equation (3.8), the total system noise can be given by

\[ N_{01} = KT_s. \]  

(3.9)

This is a very important result. It shows that in order to have low system noise temperature, the first stage should have high power gain as well as low noise temperature. This result may be generalized to any number of stages in cascade [11].

The system noise temperature of more than two amplifiers in cascade can be given by

\[ T_s = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + ... \]  

(3.10)

### 3.2.3 Noise Temperature of Absorptive Networks

A network which contains resistive elements is considered to be an absorptive network. Since an absorptive network contains resistance it generates thermal noise. Transmission lines, feeder lines and waveguides are some of the examples of the absorptive networks. Feeder line is generally used to connect to the satellite antenna. The effective noise temperature of an absorptive network is directly related to the power loss \( L \).

Consider an absorptive network which has a power loss \( L \). The power loss is the ratio of the input signal power to the output signal power. It is always greater than unity. From [1], the effective noise temperature of an absorptive network is
3.3 Antenna Temperature

Antennas operating in the receiving mode introduce noise in the satellite circuit. The temperature associated with the noise at the terminals of the antenna is known as antenna temperature. We can think of it as the effective noise temperature of the antenna. The noise energy due to the antenna temperature is the weighted average of the noise sources the antenna is looking at. The weighting factor depends upon the directivity towards a specific noise source. Antenna temperature is due to the presence of radiations in the antenna environment and antenna losses. It is important to note that the antenna temperature is not the physical temperature of the antenna. The antenna temperature is usually calculated experimentally. But, it is possible to find an upper bound on the antenna temperature depending upon the scenario.

Under Rayleigh-Jeans approximation ($h\nu << KT$), the antenna temperature is given by

$$T_A = \frac{1}{4\pi} \int_{\Omega} G(\theta, \phi) T_B d\Omega,$$

(3.12)

where $G(\theta, \phi)$ is the radiation pattern of the antenna and $T_B$ is the brightness temperature.
3.3.1 **Brightness Temperature**

Brightness temperature is the physical temperature that black body in thermal equilibrium would have to be in order to radiate the same power as of the non-black body at a frequency \( v \). Brightness temperature of a body varies with the frequency. At any temperature and at any frequency, the power radiated by a black body is more than a non-black body. As a result, the brightness temperature of a noise source is always less than its physical temperature.

In the case of large bright noise object, the antenna temperature due to the noise source is equal to its brightness temperature. Figure 3.4 depicts a large bright noise source with brightness temperature \( T_B \). The antenna temperature for a large bright noise source is independent of the radiation pattern and the distance between the antenna and noise source.

![Figure 3.4: Large bright noise source with brightness temperature \( T_B \) [2]](image)

However, antenna temperature does depend upon the distance and the radiation pattern in the case of small bright objects. Figure 3.5 shows a small bright object. It is very evident from Figure 3.5 that if the distance between the noise source and antenna changes the solid angle (\( \Omega_B \)) subtended by the noise source at the antenna will change. The antenna temperature due to a small bright noise source
Chapter 3. Noise in Terahertz based ISL

3.3. Antenna Temperature

is given by

\[ T_A = \frac{\Omega_B}{\Omega_A} T_B, \]  

(3.13)

where \( \Omega_A \) is the solid angle of the main lobe of antenna.

![Figure 3.5: Small bright noise source](image)

Now we will look at some of the possible noise sources which could contribute towards antenna temperature in THz based ISL.

### 3.3.2 Cosmic Microwave Background Radiation

Cosmic Microwave Background Radiation (CMBR) fills the entire universe and is the leftover radiation from the big bang. According to Big Bang, initially the universe was filled with hot plasma of particles (protons, neutrons and electrons) and photons (light). For the first 380,000 years the photons were interacting with electrons and were not able to travel long distances. However, the universe expanded and the temperature came down to 3000 kelvin. Now the protons and electrons were able to combine to form hydrogen atoms. In the absence of free electrons, the photons were able to travel more distances and thus the universe became transparent. Over the billions of years, universe has expanded and cooled greatly and the temperature has reduced to 2.7 K.

In 1989, NASA sent a Cosmic Background Explorer (COBE) to study about CMBR. The key discovery was that CMBR was found to be extremely precisely to a so called black body at a temperature of 2.73 K. Since the peak of CMBR lies...
in the microwave region, the brightness temperature at THz frequencies due to CMBR is very less. Needless to say, the brightness temperature of CMBR cannot go above 2.73 K. As a result, the impact of CMBR on THz based ISL is negligible.

### 3.3.3 Thermal Radiation

Any body above a temperature of 0K, emits out electromagnetic radiation. These radiation are known as thermal radiation. These radiations are generated due to the motion of the charged particles in the matter. Some of the examples of thermal radiation are infrared light and visible light. The peak of the thermal radiation depends upon the temperature of the object. The peak lies in infrared region at room temperature (290 K). Thermal radiation from the Earth has considerable impact on satellite antennas. This is because satellite antennas generally point towards the earth. As a result, they receive full thermal radiation from it. Since the size of satellite antenna is very small in comparison to the size of the noise source, i.e., Earth, the antenna temperature due to the thermal radiation from Earth is considered to be 290 K which is the physical temperature of the Earth.

### 3.3.4 Sky Noise

A body which absorbs radiation also emits out radiation. The amount of the radiation a body emits depends upon the absorptivity of the body. A perfect black body has emissivity and absorptivity both equal to 1. Consider, e.g., there is no atmosphere and the antenna at the earth station is pointing towards the space. In this case the only noise source the antenna is looking at is the cosmic noise, and the antenna temperature would be 2.7 K. But since the atmosphere absorbs radiation, it also emits some radiation of its own. These radiation acts as noise at the antenna and contribute significantly to the antenna temperature. This contribution is known as sky noise. Sky noise depends upon the frequency
and the direction at which the antenna is pointing.

Figure 3.6 depicts the antenna temperature due to the sky noise for an earth station antenna. The lower graph is for the antenna pointing directly overhead while the upper graph is for the antenna pointing just above the horizon. The difference between the two curves is due to the thermal radiation from the Earth at 290 K. When the antenna is pointing to zenith, then antenna temperature is only due to the sky noise. However, when the antenna points towards the horizon then due to the thermal radiation from the earth the antenna noise temperature increases.

![Antenna Temperature Diagram](image)

Figure 3.6: Antenna temperature of an ideal ground based antenna. The antenna is assumed to have very low beamwidth without losses and sidelobes.

Notice the two peaks in the antenna noise temperature above 10 GHz. These peaks are due to resonant losses in the Earth’s atmosphere by $H_2$ and $O_2$. In the case of rainfall, the atmospheric absorption is even more and hence the antenna noise temperature increases. We can say that rainfall degrades the transmission in two ways, it attenuates the signal as well as it introduces noise in the system.
3.4 Total System Noise

In this section we will calculate the overall system noise temperature. The constituent elements of the receiving satellite are divide into antenna element, the feeding section (outside the satellite), the feeding section (inside the satellite) and the receiver (inside the satellite). Using equations (3.6, 3.10, 3.11) and as mentioned in [26], the total system noise can be given by

\[ T_{sys} = T_A + (L_1 - 1)T_1 + L_1(L_2 - 1)T_2 + L_1L_2(NF - 1)T_0, \]  

(3.14)

where \( T_A \) is the antenna temperature, \( T_1, T_2, T_0 \) are the physical temperature of the feeder line (outside the satellite), feeder line (inside the satellite) and the receiver respectively. \( L_1 \& L_2 \) are the loss in the feeding section (outside the satellite) and feeding section (inside the satellite) respectively, and NF is the noise figure of the receiver. We will be using this equation to calculate the total noise power generated in THz based inter-satellite communication.

Now the total noise power \( P_n \) at the receiver can be readily found as

\[ P_n = KT_{sys}B, \]  

(3.15)

where K is the boltzman constant and B is the bandwidth.

It is important to note that the temperature outside the satellite depends upon the location of the satellite in the orbit. In order to find the range of the temperature outside the satellite, we first need to understand how a body attains temperature. There are three ways through which heat is transferred from one body to another.

- Conduction - In conduction there is a direct flow of heat through a body as a result of physical contact from another body. The former body can either gain or loose heat which can eventually lead to the increase or decrease in
the temperature of the body.

- Convection - In case of convection, heat is transferred to the body by the fluids such as gas or liquid. Heat transferred to the body by the collisions of the atmospheric molecules is an example of convection.

- Radiation - In radiation mechanism heat is transferred to a body using electromagnetic wave. It does not require any material medium for transferring the heat.

In THz based ISL, we will be communicating in an environment where the density of the air is very low. There will be very less air molecules to transfer the heat via convection. So even though the temperature of thermosphere is 2000°C (2273 K), the temperature outside the satellite is very low. Also, the heat transfer will not take place via conduction as it requires a separate physical body for transfer. Hence, in our analysis the only way through which heat transfer can take place is via radiation. As a result, the temperature of LEO satellites vary from -170°C (103 K) to 123°C (396 K) depending upon the location in the orbit. We have to consider this wide variation in the temperature outside satellite in our link budget design as it can impact the total noise power at the receiver.

### 3.5 Signal-to-Noise ratio

The signal-to-noise ratio (SNR) is an important measure to evaluate the performance of the satellite link. It is the ratio of carrier power to noise power at the receiver input. It is given by

\[
\frac{S}{N} = \frac{P_r}{P_n},
\]  

(3.16)
where $P_r$ is the received power and $P_n$ is the noise power. This equation can also be expressed in decibels (dB)

$$\left( \frac{S}{N} \right)_d = P_{rdB} - P_{ndB}. \quad (3.17)$$

Using equations (2.6, 3.14, 3.17), we can rewrite the $\frac{S}{N}$ ratio as

$$\left( \frac{S}{N} \right)_d = P_{tdB} + G_{tdB} + G_{rdB} - L_{dB} - K_{dB} - T_{sysdB} - B_{dB}. \quad (3.18)$$
CHAPTER 4

Link Budget Analysis

From the information we have gained from the previous chapters, in this chapter we will be devising link budget for THz based inter-satellite communication. We will begin by calculating the gain of the transmitter and receiver antenna required to compensate for the high propagation loss occurring due to the transmission at THz frequencies. We will also calculate the beam width corresponding to the gain, and then we will perform a comparative analysis on the basis of the pointing requirements between Optical and THz based ISL.

For link budget analysis, we will make use of the Friis Propagation model developed in Chapter 2. For calculating the noise power we will be making use of the total system noise temperature equation developed in Chapter 3.

The recent advancements in the terahertz technology, such as III-V semiconductor technologies in an electronic approach and Quantum Cascade Lasers in an optics approach, allows us to generate frequencies from 0.34 THz to 1 THz with a power of 1 mW to 10 mW [4][18].

We will divide the analysis into two parts depending upon the transmit power, carrier frequency and location of the satellite in the orbit. We desire to achieve an
SNR of 10 dB at the receiver. At first, we will find the lower bound on the gain of the antenna required to maintain an SNR of 10 dB at the receiver. We will do the analysis by choosing three different values of the bandwidth. In the same way, we will be finding an upper bound on the gain of the antenna with respect to distance.

### 4.1 Antenna Gain Required - Lower Bound

For lower bound analysis the temperature outside the satellite is taken to be -170°C (103 K). This is because as we decrease the temperature the noise power decreases and the signal to noise power ratio increases. Hence, we would require less amount of gain of the antenna to achieve the same SNR.

Table 4.1 indicates the parameters considered in the lower bound analysis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_s$</td>
<td>10 mW</td>
</tr>
<tr>
<td>$f_c$</td>
<td>0.34 THz</td>
</tr>
<tr>
<td>$T_A$</td>
<td>300 K</td>
</tr>
<tr>
<td>$L_1, L_2$</td>
<td>1.3 dB</td>
</tr>
<tr>
<td>$T_1$</td>
<td>103 K</td>
</tr>
<tr>
<td>$T_2$</td>
<td>290 K</td>
</tr>
<tr>
<td>NF</td>
<td>3 dB</td>
</tr>
<tr>
<td>$d$</td>
<td>50 km – 1000 km</td>
</tr>
<tr>
<td>$B$</td>
<td>1 GHz, 5 GHz, 10 GHz</td>
</tr>
</tbody>
</table>

Table 4.1: Parameters - Lower bound
Gain Required

From Figure 4.1, we can see that as the distance increases the gain required to achieve SNR of 10 dB also increases. This is due to the increase in the propagation loss with the distance. The total system noise temperature is found to be 683.1 K. We can also see that the gain required is the highest in the case when the bandwidth is 10 GHz. This is because the total noise power is directly proportional to the bandwidth. As a result, we will need more gain of the antenna to achieve SNR of 10 dB.

Beamwidth

The beamwidth, also known as half power beamwidth (HPBW), is the angle between the half power points (-3 dB) of the main lobe. In this section, we will calculate the upper bound on the HPBW corresponding to the gain of the transmitter and receiver antenna calculated in previous section. From [20], the
gain of the antenna is related to the half power beam width as

\[ G \leq \frac{32400}{\theta \phi}, \]  

(4.1)

where \( \theta \) is horizontal beamwidth in degrees and \( \phi \) is the vertical beamwidth in degrees. Horizontal and vertical beamwidth are the angles in the horizontal and vertical plane where the power of the main lobe is reduced by half. We will assume the horizontal and vertical beam width to be equal in our analysis. The relation between HPBW and gain of the antenna can now readily found to be

\[ \theta_d = \sqrt{\frac{32400}{G}}, \]  

(4.2)

where \( \theta_d \) is the HPBW in degrees.

From Figure 4.2 we can see that as the distance between transmitter and receiver increases the upper bound on the HPBW decreases. This is due to the
inverse relationship between the gain and the HPBW. It is important to note that as the HPBW decreases it becomes difficult to aim at the receiver. Hence, there is a need for an accurate pointing system for communicating with the receiver.

**Beam Diameter**

Using geometry, the beam diameter at a particular distance \( d \) of an antenna beam with HPBW \( \theta_d \) can be readily found as

\[
Beam diameter = 2dsin\left(\frac{\theta_d}{2}\right).
\]

(4.3)

![Figure 4.3: Beam diameter vs Distance (Lower Bound)](image)

From Figure 4.3 we can see that the beam diameter is increasing with distance. It is very important to note that even though the HPBW is decreasing the beam diameter is increasing and it is of the order of kilometer (km).
Chapter 4. Link Budget Analysis 4.2. Antenna Gain Required - Upper Bound

4.2 Antenna Gain Required - Upper Bound

In the same way we will repeat the calculations when the temperature outside the satellite is 123°C (396 K). In upper bound analysis we will consider the transmit power to be 1 mW and the carrier frequency to be 1 THz.

Table 4.2 indicates the parameters considered in the lower bound analysis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_t$</td>
<td>1 mW</td>
</tr>
<tr>
<td>$f_c$</td>
<td>1 THz</td>
</tr>
<tr>
<td>$T_A$</td>
<td>300 K</td>
</tr>
<tr>
<td>$T_1, T_2$</td>
<td>1.3 dB</td>
</tr>
<tr>
<td>$T_1, T_2$</td>
<td>396 K, 290 K</td>
</tr>
<tr>
<td>$N_F$</td>
<td>3 dB</td>
</tr>
<tr>
<td>$d$</td>
<td>50 km – 1000 km</td>
</tr>
<tr>
<td>$B$</td>
<td>1 GHz, 5 GHz, 10 GHz</td>
</tr>
</tbody>
</table>

Table 4.2: Parameters - Upper bound

Figure 4.4: Gain required for SNR of 10 dB vs Distance (Upper Bound)
Figure 4.5: Beamwidth vs Distance (Upper Bound)

Figure 4.6: Beam diameter vs Distance (Upper Bound)

The effective noise temperature in the upper bound analysis is 712.4 K. On
4.3 Terahertz ISL vs Optical ISL

In this section, we will do a comparative analysis between the THz based ISL and optical/laser based ISL. This comparison will be done on the basis of pointing requirements in both the cases.

From [21], the beam diameter of a gaussian laser beam at a position $z$ is given by

$$w(z) = 2w_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2},$$

(4.4)

where

$$z_R = \frac{\pi w_0^2}{\lambda},$$

(4.5)

and $z$ is the axial distance, and $w_0$ is the waist size. Waist size is the radius of the laser beam at its narrowest point.

In our analysis, we will consider a red laser with wavelength of 650 nm. We will assume the waist size to be 1 cm. This value is deliberately taken to be large in order to show the big difference in the beam diameter of THz based ISL and optical/laser based ISL. We will calculate the beam diameter for the same range of distances, i.e., 50 km to 1000 km.
From Figure 4.7, we can see that the beam diameter is very less in the case of optical/laser based ISL. Also, from Figure 4.8 the beam diameter in lower bound analysis and upper bound analysis at 10 GHz is much higher than the beam diameter in optical/laser based ISL. As a result, pointing requirements in the case of optical/laser based ISL will be very high in comparison to THz based ISL. We will need a highly accurate ATP subsystem in order to communicate with the receiver. Thus, we can say that the efficiency of THz based ISL is more in comparison to optical based ISL.
In this chapter, we devised link budget analysis and calculated the gain of the transmitter and receiver antenna required to achieve an SNR of 10 dB. In the worst case scenario of maximum distance between satellites (1000 km), maximum noise temperature of 712.4 K, transmit power of 1 mW, carrier frequency of 1 THz and bandwidth of 10 GHz, we have found the gain required to be 76 dB. This high gain of the antenna can be achieved by using an array or reflector antenna. A mechanically scanned confocal ellipsoidal reflector antenna system was reported in [22]. The simulation results show to achieve a gain of 75 dB at 0.67 THz.
CHAPTER 5

Additional Challenges in THz based ISL

In this chapter we will look at some of the additional challenges that needs to be addressed in THz based ISL. We will begin by looking at the possibility of multipath propagation due to the presence of debris in the space and its impact on the quality of communication. We will also consider the impact of the high relative motion between the satellites.

5.1 Space Debris

Space debris is the collection of non-functional human made objects in the earth orbit such as old satellites, fragments from disintegration, erosion and collisions. As of July 2013, more than 170 million debris smaller than 1 cm, about 670,000 debris 1-10 cm, and around 29000 larger debris were estimated to be in orbit. Most of these debris are present in LEO and MEO [23]. In our analysis, we are making use of THz radiation which means a wavelength of around $10^{-4}$ m. From Sec.2.4, we can say that the scattering which will occur due to the space debris will be geometric scattering. We need to take into account the reflections which
will occur due to the space debris which can lead to multi path propagation.

In the next section, we will develop a simulation model for the multi path propagation due to space debris in THz based ISL.

### 5.1.1 System Model

To model the number of multipath components, we need to take into account propagation loss, the geometry of the network and the density of space debris.

**LOS & NLOS propagation loss**

Using equation (2.5), we can say that the total path loss for the line-of-sight (LOS) component can be given by

\[
PL_{LOS}(f, d) = \left(\frac{4\pi fd}{c}\right)^2,
\]

(5.1)

where \(f\) is the operating frequency in Hz, \(d\) is the separation between the transmitter and receiver, \(c\) is the speed of light in free space.

For the components which are not in line-of-sight (NLOS), we need to account for the reflection loss which occurs when the signal collides with an obstacle. In this case, the total path loss can be given by

\[
PL_{NLOS}(f, d) = \left(\frac{4\pi fd}{c}\right)^2 \gamma(f),
\]

(5.2)

where \(\gamma(f)\) is the reflection coefficient.

**Network Topology**

The origin of the coordinate system is assumed to be at the mid-point of the distance between two satellites. The transmitting and receiving satellites are placed at equal distance \(d/2\) from the origin on the x axis. We consider directional antennas
are deployed at both the transmitter and receiver with $\theta_d$ as the beamwidth. We also consider that different obstacles are randomly distributed in the space by following a spatial Poisson process with rate $\lambda$. Since poisson process is a stationary independent increment process, the probability of finding $k$ objects in the area $A$ is given by

$$P(k \in A) = \frac{(\lambda A)^k}{k!} e^{-\lambda A}. \quad (5.3)$$

As shown in Figure 5.1, due to an obstacle (space junk) at point A there is reflection of the signal. As a result, another copy of the same transmitted signal is received at $R_x$. In our analysis, we have considered only single bounce reflections.

### 5.1.2 Simulation Model

In this section we will perform simulations to find out the number of multipaths due to space debris in THz based ISL with respect to time. We chose the frequency
at which we are transmitting to be 0.34 THz. The value of of beamwidth is considered to be 0.5 degree. The distance between the satellites is considered to be 1000 km. Also, the value of reflection coefficient is considered to be 1. The final result was found by taking 1000 realizations of the system. The simulation result is calculated by plotting the histogram of the number of multipaths with time.

In our analysis we have considered the density of the space debris to be \(10^{-9}\) per \(m^2\). We can see from the Figure 5.2 all the space debris that are enclosed in the receive and transmit beam. These space debris will lead to multipath propagation.

Figure 5.2: Space debris enclosed in Transmit & Receive Beam, \(\lambda = 10^{-9}\) per \(m^2\)
Chapter 5. Additional Challenges in THz based ISL

5.1. Space Debris

Figure 5.3: Multipath components as function of path delay, $\lambda = 10^{-9}$ per $m^2$

From Figure 5.3, we can see that as time increases the number of multipath decreases. We can observe that the first path arrives at the receiver at time 3.33 ms. This is because we have considered distance between transmitter and receiver to be 1000 kilometer and the speed of light is $3 \times 10^8$ m/s. This plot is drawn by calculating the total distance traversed by the signal from the transmitter to the receiver via the reflector. This total distance is divided by the speed of light to calculate the time at which signal will arrive at the receiver. After that a histogram is plotted for all the multipaths. This experiment is conducted 1000 times to calculate the average number of multipaths with time.

The model that we have developed in this chapter is very general which means that it is independent of the technology used in PHY layer. This model can also be extended to terrestrial environment with directional antennas. However, the model that we have described above will change in the case of a bounded area application.
From Figure 5.3, we can also see that the delay spread is about 0.1 μs. As mentioned in Chapter 2, a high delay spread can lead to Intersymbol Interference (ISI). ISI happens when the duration of the signal that we are transmitting is less than the delay spread. In our scenario, since the bandwidth is in the order of GHz, the duration of the signal will be of the order of nanoseconds. As a result, there are chances of ISI in THz based ISL. So we need to take into account the impact of space debris on the quality of the link.

5.1.3 Power Delay profile

In this section, we will develop a power delay profile for THz based ISL in presence of space debris. In order to find the power delay profile we need to know the probability that any multipath component does not get blocked in the way while reaching at the receiver. We will consider the obstacles to be of circular shape with radius r and they follow the same Poisson distribution as mentioned in Sec. 5.1.1. As described in [18], the probability that the signal does not get blocked in the way while reaching at the receiver is given by

\[ P_{NB}(d) = e^{-\lambda(rd+\pi r^2)}, \]  

(5.4)

where \( r \) is the radius of the object and \( d \) is the distance traveled by the multipath component from the transmitter to the receiver. The power delay profile can now be readily found by

\[ PDP(\tau) = \frac{PL_{NLOS}(f, c\tau)}{N(\tau)P_{NB}(d = c\tau)}. \]  

(5.5)

In our analysis, we have assumed the radius of the obstacles to be 5 cm and the carrier frequency is taken to be 0.34 THz.
Figure 5.4: Power delay profile vs time

From Figure 5.4, we can say that the power received at the receiver is decreasing with time. This is because the multipath components which are arriving late at the receiver are traveling more distance. Furthermore, the number of multipaths are also decreasing with time.

5.2 Doppler Spread

Another major challenge that we need to take care in THz based ISL is the issue of doppler spread due to the high relative motion between the satellites. Doppler effect occurs when the receiver or the transmitter is moving with respect to the wave source. In this scenario the frequency received at the receiver is not the same as the source. If the transmitter and receiver are moving towards each other then the frequency of the EM wave at the receiver increases. On the other hand, if the transmitter and receiver are moving away from each other then the frequency of the EM wave at the receiver decreases. The frequency of the received signal $f_R$
can be given by

\[ f_R = f_C - f_D, \] (5.6)

where \( f_C \) is the transmitter frequency and \( f_D \) is the doppler frequency. The doppler frequency is given by

\[ f_D = \frac{v}{\lambda}, \] (5.7)

where \( v \) is the relative speed in the moving direction and \( \lambda \) is the wavelength of the EM wave.

In our analysis, the impact of the doppler spread can be very significant. This is because the relative speed at which the satellites move can get very high. Furthermore, we are transmitting at very low wavelength of about 30 \( \mu \text{m} \) to 3000 \( \mu \text{m} \). This high speed of the motion between the transmitter and receiver leads to change in the impulse response of the channel. If the time within which the channel changes is more than the duration of the signal then channel is considered to be slow fading channel. On the other hand, if the channel response changing time is less than the duration of the signal then the channel changes during the transmission of the signal and there is distortion at the receiver. This channel is considered to be fast fading channel.

In order to find the maximum duration of the signal that can be transmitted without distortion at the receiver, we define a measure called coherence time. Coherence time is the statistical measure of the time duration over which the channel impulse response is considered to be not varying.

Coherence time is related to the doppler frequency and is approximately given by

\[ T_c = \frac{9}{16\pi f_D}, \] (5.8)

where \( f_D \) is the doppler frequency.

As calculated in [24], the maximum relative speed between satellites can go
as high as 8 km/sec. In our analysis we are making use of $f_c = 0.34THz$. Using equation (5.7), we can calculate the doppler frequency to be 9 MHz. We can use this value to calculate the coherence time. The value of the coherence time is around 0.02 $\mu s$. Thus, if we want to transmit a signal without distortion at the receiver the duration of the symbol should be less than 0.02 $\mu s$. In our analysis, we used the transmission bandwidth to be 1 GHz, 5 GHz and 10 GHz. Since the duration of the signal has an inverse relationship with the bandwidth, the duration in our case would be of the order of nanoseconds. As a result, we will not be facing the issue of fast fading at the receiver. However, we still need to compensate for the doppler spread at the receiver.
Conclusions and Future Work

In this research, we studied the feasibility of THz band for Inter-satellite communication. We developed the propagation model and analyzed the factors which can affect THz wave propagation in ISL. We also studied about the noise sources which can impact the quality of the signal. In order to maintain a specified quality of the link, we calculated the gain of the antenna required at the transmitter and receiver in the worst case scenario. Based upon the pointing requirements, a comparative analysis between laser based ISL and THz based ISL was also conducted and it was shown that the latter has more efficiency. Lastly, we analyzed the impact of space debris leading to multipath propagation and doppler spread on THz based ISL.

As part of future work, we need to design the modulation techniques to be used for implementing THz based ISL. Also, the value of beamwidth required to maintain the quality of the link is low, as a result, an accurate tracking and pointing subsystem needs to be implemented on the satellites. Furthermore, we need to properly choose high gain antennas considering the budget on the size of the payload.
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