

LINK DESIGN FOR LOW POWER DIRECT ACCESS TO GEO SATELLITE BASED IoT SYSTEMS

THESIS REPORT

*Submitted in partial fulfillment of the requirements for the award of the
Degree of Master of Technology in Electronics and Communication
Engineering with specialization in Communication Systems by the
A P J Abdul Kalam Technological University*

by

JOMY JACOB

Reg.No TKM21ECCS06



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CERTIFICATE

Certified that this Project report titled “**LINK DESIGN FOR LOW POWER DIRECT ACCESS TO GEO SATELLITE BASED IoT SYSTEMS**” is a bonafide record of the work done by **JOMY JACOB** (Reg.No.TKM21ECCS06) under my supervision, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electronics and Communication Engineering with specialization in Communication Systems by the A P J Abdul Kalam Technological University.

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ABSTRACT

The design of satellite communication system is a complex process requiring compromises between many factors to achieve the best performance at an acceptable cost. In the present world GEO satellites carry the vast majority of the world's satellite traffic, therefore it becomes very important for the link designer to design for optimum utilization of space segment. Internet of Things (IoT) is developing at an impressive speed, and the range of applications for IoT is becoming wider. Long Range (LoRa) technology is currently one of the most promising terrestrial Low-Power Wide Area Network (LPWAN) technologies.

LoRa technology has become popular candidate technology for IoT satellites. Its advantages are low power consumption, inexpensive equipment and most importantly, appropriate for long range communication. In this work datas of LoRa and GEO satellites are collected and with the help of link budget modelling, the effectiveness in establishing successful communication link between GEO satellite and IoT power class 1 device communicating in 2.4 GHz Industrial, Scientific, Medical (ISM) frequency band are evaluated. Findings indicated that for an orbital altitude up to 35000km communication with power class 1 device (35dBm) is feasible.

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Chapter 1

Introduction

Communication technology has advanced in the new era of IoTs, making it possible to use communication technology in a variety of scenarios, but there are some scenarios or areas where traditional IoT fails to meet needs. As a result, LoRa, a spread spectrum modulation technique derived from chirp spread spectrum technology, has been applied to this problem due to its long-range communication capability, low power consumption, and long lifetime. Due to this global adoption of LoRa networks will increase, and LoRa gateways may not be able to support widespread use. This issue will be resolved if a LoRa node can be modelled to work with Geo stationary Earth Orbit (GEO) satellites and can design LoRa ground sensors that can communicate data to satellites.

The LPWAN communication technologies available includes Sigfox [1] Narrow-Band IoT (NB-IoT) [2], Weightless [3] and Random Phase Multiple Access (RPMA) [4] and LoRa [5]. LoRa uses unlicensed spectrum and operates within the Industrial, Scientific and Medical (ISM) band. The LoRa comprises of two layers which are physical layer (PHY) and Media Access Control (MAC) layer. LoRa PHY has several parameters that needs to be configured for optimal performance. These parameters include bandwidth, spreading factor, coding rate, carrier frequency and transmission power. In the MAC layer, LoRaWAN protocols allows for several End Nodes (EN) to communicate with the GateWay (GW). The open standard and open business model of LoRa has made it attractive and has enabled its deployment for different IoT use cases.

Currently, there are a IoT standards, protocols, and communication mechanisms that promise to more or less solve the main problems of IoT. The main characteristic of this concept is that it provides communication capabilities to a wide number of sensors distributed over a large-scale geographic area. The challenges are great, taking into consideration the fact that the communication distance is limited by the resources available to these sensors (e.g., processing power, information storage, and energy resources). Also, to ensure the highest performance level possible, as well as the integration of a large number of sensors, intensive research focusing on streamlining and improving the communication mechanism is required.

This project work presents a link budget analysis for GEO satellites based IoT systems which evaluates the feasibility of successful communication link establishment between a LoRa ground sensor and a LoRa gateway which is mounted on an IoT satellite, considering the geometry and link budget components along with LoRa specifications, that communicate based on the AS923 plan or the LoRa frequency band 923 – 925 MHz (More specifically- 923.2 MHz channel) that can provide coverage up to an orbital altitude of 6978Km and further on increasing the operating frequency of IoT device to 2.412GHz band leading to successful establishment of reliable communication link to GEO satellites.

Chapter 2

Literature Review

This section, presents an overview of some works related to the proposed approach. Sanctis et. al., [6] presented ongoing research works on satellite communication based on IoT and M2M applications such as development of MAC protocols for accessing satellite resources to sensor network, use of Internet Protocol Version (IPV6) over satellite, interoperability between terrestrial and satellite networks, resource allocation and transmission management for group based communication. Satellite play a key role in the sectors like smart grid, environmental monitoring and emergency management. Direct and indirect access are two modes taken of interconnecting satellite with sensor/actuator node in Wireless Sensor Area Network (WSAN). The sensors and actuators that were deployed on a wide area communicating with satellites via direct and indirect way (Using a sink node), in which the collected data were transferred to internet for the ease of accessing by the user located at another area. The data are forwarded which is used to provide group oriented services to support M2M communication and it is useful in all critical situations. The authors concluded that S-IoT can made more effective by extending the range of IoT devices to higher orbital altitudes.

Marchese et. al., [7] developed a prototype that deploys IoT communication protocol (LoRa-WAN) gateway on a Unmanned Aerial Vehicle (UAV) which is communicating with the IoT devices through a simulated satellite link resulting in extending the coverage of LoRa and data exchange between multiple IoT device on a smart agri-

culture scenario. For experimentation a smart agriculture scenario were developed initially (A test bed that consisting of an IoT device). For sensing the physical quantity, IoT gateway (LoRa-WAN gateway is placed on a UAV which collects data while flying), satellite (establishes connection between IoT gateway with Internet), LoRa-WAN cloud platform (for storage of data and for later retrieval when needed) were used. To provide immunity against noise chirp spread spectrum modulation is used and it determines the code rate, maximum achievable data rate for transmission. Experimentation were done on in-lab and on-field in which the Received Signal Strength Indicator (RSSI), SNR, delivery time were evaluated. The results of the proposed models shows that the gateway keeps forwarding data in all situations, indicating the resilience and system tolerance.

Krondrof et. al., [8] proposed a system designed for ICARUS, a kind of sensor used for monitoring the health of wildlife, collecting the data and transmitting it globally. Random Access-very Low Power Wide Area Network (RA-v LPWANs) are used in International Community for Animal Research Using Space (ICARUS) to solve the problems hampering conventional LPWAN IoT systems while applying to space communications. “TAGS” which acts as a mini transmitter of the collected information, it’s SNR, Doppler shift, multipath propagation, orthogonality among tag signals are major challenges that was addressed in the paper.

Prior to transmission a complex wakeup procedure having 6 individual steps were done and exact data transmission time were estimated. Uplink and downlink frame structures that contain 2 preambles that is used for time and frequency synchronization namely Signaling, Synchronization-preambles. Channel estimation circuitry was used by the International Space Station (ISS) Spacecraft for finding the channel impulse response and channel equalization is done by rake receivers at the tags. The author estimates overall performance of tag transmitter that pass 20 sets of position data to International Space Station during each overhead flight on a short contact window of 8 seconds indicates the robustness of the modelled device.

Manzoor et. al., [9] posited a probability of Line-of-Sight (LoS) which was used as the basics for a framework for adopting frame repetitions where numerous redun-

dant data transmissions were added to increase its success rate for GEO synchronous equatorial orbit. The framework also analyses the coverage performance (Probability) of IoT devices in terms of frame success rate for tuning the repetition behaviour for a specific satellite admittance region. An analytical framework was developed for modelling frame repetition in terms of line-of-sight probability using techniques from stochastic geometry. Maximum zenith angle, minimum elevation angle (IoT devices with very low elevation angles were assessed to have extremely poor radio connection performance, which limits the admittance zone of IoT devices and lowers the probability of successful transmission) were defined.

The influence of probability of Line-of-Sight (p-Los) on path-loss and probability of successful transmission were examined. Probability of non line of sight (depends on duty cycle, tuning factor 'alpha', controllable modelling parameter 'beta') were derived to find the number of transmission repetitions. The success probability of a frame delivery in a constellation of k satellites with non-overlapping spots were derived, and the global average success probability was evaluated for a specific tuning factor and minimum elevation angles. Author notifies that an optimal combination values (optimization) exist for Theta-min, and 'alpha' so that a better global average success probability can be achieved for frame repetition technique and the application of this on network designing to design the network according to operating parameters.

Nandra et. al., [10] focused on a study regarding the significance of some factors that go into link budget calculation and assesses complete physical change impacting the entire link budget profile. Multiple access modes, atmospheric propagation effects, and frequency bands all have an impact on the satellite communication system designing. Satellite information such as orbital location, figure of merit, surface flux density, saturation Effective Isotropic Radiating Power (EIRP) are considered. Link parameters such as data rate, Forward Error Correction (FEC) code rate, transmission rate, SNR were focused. Trans-station, receive station, losses associated with it are used to evaluate uplink, downlink and overall link analysis. As the variation on Block Error Rate less it's effect on required C/N, trans earth station EIRP, satellite downlink EIRP will be more. Author pointed out that Satellite link quality are improved by using high quality antennas with better gain along with less pointing error

and suggested the requirement of balance among all parameters for getting optimum performance.

Wei et. al; [11] proposed a scheme for satellite IoT edge intelligent computing and evaluated the importance of edge computing and deep learning on target detection from the picture captured by satellite. The ground cloud centre, satellite IoT edge node, and satellite IoT cloud computing system are the three components of the satellite IoT cloud edge computing system. In addition to job offloading capabilities, satellite IoT cloud nodes have storage and processing capabilities. A satellite IoT cloud node serves as a data centre for the IoT. These two nodes can operate in a geosynchronous orbit or the same orbit. The satellite receives training for the deep learning target detection model beforehand. Author highlights the key benefits of the suggested approach which include lower data transmission from satellites, reduced data processing and delay, bandwidth savings, improved bandwidth utilisation for intersatellite communications, and lessened demand on satellite ground station data processing.

Knoop et. al., [12] proposed a waveform named Unipolar Coded Chirp Spread Spectrum (UCSS) that enables ultranarrow band communication between IoT devices and GEO satellites with random multiple access at higher frequency (C-band and above). Integration of LPWAN with IoT device and giving link to the satellite improves its application on wide area. For Machine Type Communication (MTC) at low rate via satellite, Scramble Coded Multiple Access (SCMA) with spreading and multiple access is used known as Non Orthogonal Multiple Access (NOMA). Link power Budget for a satellite link at Ku band (14GHz) were designed for an achievable data rate. The feasibility of ultra-low-rate communication with UCSS is demonstrated by Over The Air (OTA) demonstration. Author conveys that the Waveform will reduce interference with other users, and is suitable for random multiple access along with capability to handle multiple users transmitting data simultaneously in a random multiple access scheme enabling better acquisition of signal in the presence of phase noise.

Chapter 3

Proposed Methodology

3.1 LoRa Sensor on a Big Scale for Long Distance Transmission

The LoRa modulation uses a modified frequency modulation (Frequency-Shift Keying) that allows data to be transferred over a range of tens of kilometers. Fig. 3.1. shows the LoRaWAN (Long-Range Wide Area Network) protocol defined by the LoRa Alliance.

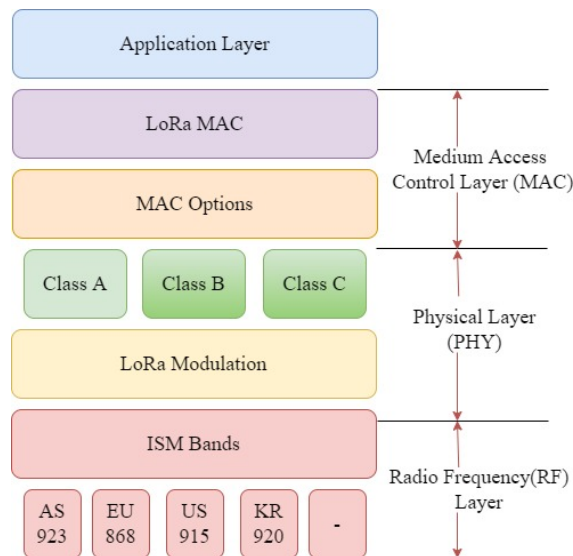


Figure 3.1: LoRaWAN communication protocol stack

The Semtech-patented LoRa modulation is used at the physical level. LoRa runs

in the ISM frequency band, which depends on the location of the sensors. There are no additional licence fee payments because LoRa sensors operate in the ISM license-free frequency, which is a benefit. Above the MAC level, application layer is defined by the users. Since the technology is not linked to a mobile network provider, there is a chance that users will apply it in an open-source way.

LoRa is a low power protocol that provides communication between sensor node to internet with low power consumption [13]. It can provide a range of 15 km in urban environment conditions and much longer in rural areas [14]. The LoRaWAN architecture consist of sensors and a gateway module meant to centralize and collect messages received from various sensors. When a LoRa node transmits a packet, the gateway module receives it and delivers it back to the network server. The latter centralises and manages the entire LoRaWAN network and is in charge of transmitting MAC commands meant to boost the architecture's performance. When creating a LoRa network, it is essential to accurately regulate the sensor's parameters. [15].

The user interface application is situated on the application server, which is the level from which the user can request and view various reports in order to query the data. Because the gateway modules can connect with several sensors at once, this architecture's key benefit is that it can integrate a lot of sensors. The architecture of the network is comparable to cellular networks because it uses a star topology. A device needs to be capable of simultaneously receiving and monitoring all 8 channels in order to be recognised as a LoRaWAN gateway module.

Depending on the type of the application, the LoRa alliance defines three classes of sensors

- **Class A:** The sensor delivers packets to the gateway module on a regular basis. The node maintains the receiver active for a very brief time after the transmitting procedure is finished so that it can receive data from the gateway during that time. The sensor goes into sleep mode after completing this cycle in order to conserve energy. The duty cycle setting also places a limitation on how many packets a sensor can transmit in a single day.

- **Class B:** This is a kind of sensor in contrast to class A, has pre-set receiving time slots. As a result, it is active more frequently and watches for messages from the gateway module.
- **Class C:** This is the lowest energy efficiency class, because the sensor keeps the receiver constantly active, being able to receive messages from the gateway module at any time.

Spreading Factor (SF), Bandwidth (BW), and carrier frequency are the three primary characteristics that characterise LoRa technology. A compromise between emission power and distance is made in the transmission rate by applying orthogonal spreading factors. [16]. Thus, Within a communication system with a constrained frequency band, a high level of performance can be attained. Numerous papers have been published in the literature. [19]- [25] dealing with LoRa, but no one investigates the possibilities of establishing reliable communication to GEO Satellites.

The 8 uplink channels in the Asian AS 920-923 MHz ISM frequency band are separated from one another by a bandwidth of 0.2 MHz. As a result, when a sensor wishes to transmit a message, it first selects a spreading factor, a communication route, and an energy level before sending the message. The sensor opens two reception slots after transmission is complete: the first one send after the completion of the transmission process and the second one send after the previous reception slot.

All 8 communication channels can be used simultaneously by the gateway sensors to receive and send messages, and each message can be delivered using a different spreading factor. To give the sensors assurance that the packet was correctly received, acknowledgment packets might be used. The introduction of such a mechanism will definitely result in an increase in energy usage. The network server sends MAC commands to the sensors, which then use an Adaptive Data Rate (ADR) method to adjust and change characteristics like the spreading factor and the communication channel to coordinate the entire architecture. The primary goal is to raise the standard of performance. [26].

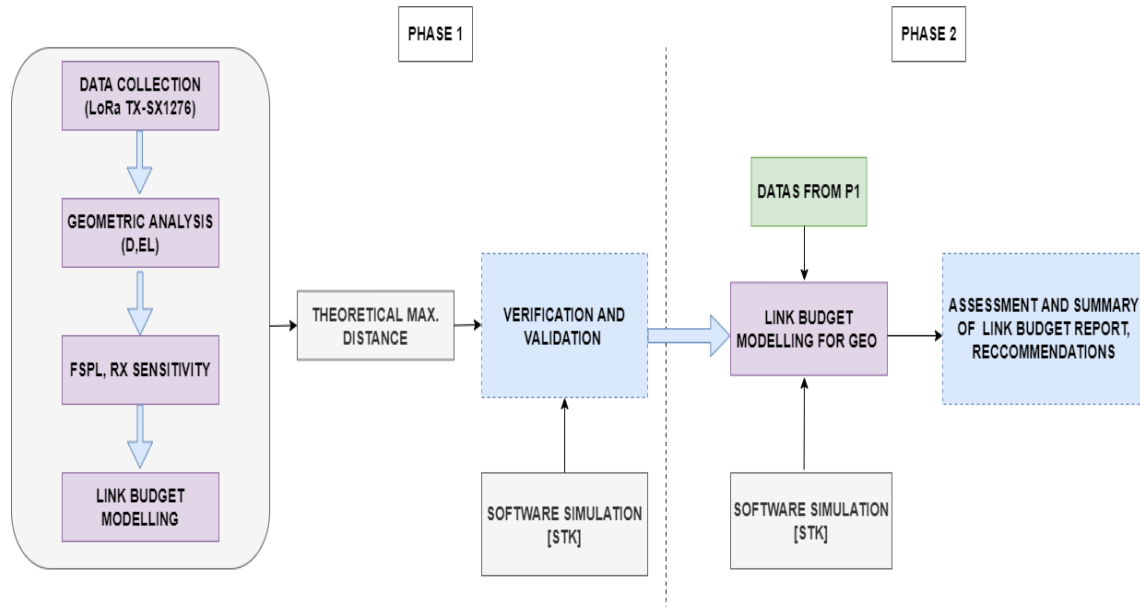


Figure 3.2: Link budget framework

It is feasible to offset the degradation brought on by the noise on the communication channel by expanding the bandwidth of a modulated signal. This is the fundamental idea behind spectral spreading. In classical transmission systems involving Direct-Sequence Spread Spectrum (DSSS), the signal emitted by the transmitter undergoes changes in accordance to a sequence of code [27]. For LoRa modulation, this procedure is often carried out by multiplying the intended data signal by a propagation code referred to as the chirp radar sequence. Because the chirp sequence moves considerably more quickly than the original data signal, the bandwidth of the signal is enhanced. As a result, spectral spreading is carried out, and interference resistance is increased.

3.2 FrameWork of link budget modelling

The framework of link budget modelling for direct access to GEO Satellite based IoT systems are divided in to two different phases namely phase1 and phase 2 as represented in the Fig. 3.2.

In the 1st phase of design, with reference to the specified scenario maximum distance up to which data can transmit from IoT device with 20dBm power (power class 5 devices) to the satellite with AS 923-925 MHz ISM frequency bands are evaluated

mathematically and it is validated and verified by software simulation.

At the second phase, certain parameters are manipulated in accordance with the conclusion extracted from 1st phase resulting in the modelling of link budget for GEO Satellites based IoT systems for arriving at a conclusion about the possibility of reliable link establishment.

3.3 Theoretical Fundamentals of Link Budget Modelling

This section contains the theoretical fundamentals that constituting the base of the link budget analysis proposed. First some important parameters are introduced in order to explain the working scenario. After that, the link budget is defined including its relationship with other link indicators.

3.3.1 Fundamentals of LoRa WAN

A low-power, wide-area networking protocol titled LoRaWAN is built on top of the LoRa radio modulation method. It manages communication between end-node devices and network gateways and wirelessly connects devices to the internet. LoRaWAN is an accessible long-range, bi-directional communication protocol with very low power consumption and is commonly used in industries and smart cities.

3.3.1.1 LoRa Transmitter SX-1276

The SX1276 transceivers feature the LoRa provides ultra-long range spread spectrum communication and high interference immunity. It can achieve a sensitivity of over -148dBm as shown in Table 3.1. The high sensitivity combined with the integrated +20dBm power amplifier yields industry leading link budget making it optimal for any application requiring range or robustness. In addition, LoRa significantly outperforms conventional modulation approaches in terms of blocking and selectivity, eliminating the customary design trade-off between range, interference immunity, and energy usage.

Table 3.1: SX-1276 transmitter specifications

SX 1276 LoRa Tx-SPECIFICATIONS	
Transmit Power	+20 dBm
Noise Figure	+6dB
Spreading Factor	6-12
Band Width (KHz)	7.8-500
High sensitivity	Up to -148 dBm
Data Rate	0.18-37.5Kbps
Connection Loss	+1dB
Antenna Gain	+2dBi
Modulation	FSK
Packet Error Rate	1%
Output Power	+13dBm
FEC	4/6
Payload Length	64 Bytes
Preamble Length	12 Symbols

3.3.1.2 LoRa spreading factors

Depending on the location or frequency plan, a LoRaWAN requires 125, 250, or 500 kHz of bandwidth with a Spreading Factor (SF) of 7 to 12 as shown in Table 3.2. Long distances are suited for a high SF. Lower transmission power can preserve battery life, but the signal’s range will be reduced. Transmission power should be adequate for a LoRa module; the majority have 20 dBm, although this can be increased as long as it stays under the limits for residential communication.

Table 3.2: LoRa range of spreading factors

Spreading Factor (RegModulationCfg)	Spreading Factor (Chips/Symbol)	LoRa Demodulator SNR
6	64	-5dB
7	128	-7.5dB
8	256	-10dB
9	512	-12.5dB
10	1024	-15dB
11	2048	-17.5dB
12	4096	-20dB

3.3.1.3 LoRa bandwidth options

The transmission time is lowered at the expense of a decreased sensitivity improvement when the signal bandwidth is increased since a larger effective data rate can be used. The bandwidth being used and the spreading factor affect the data rate. The range of bandwidth options accessible with LoRa are shown in Table 3.3. LoRaWAN

Table 3.3: LoRa accessible bandwidth

Bandwidth (KHz)	Spreading Factor	Coding Rate	Nominal Rb (bps)
7.8	12	4/5	18
10.4	12	4/5	24
15.6	12	4/5	37
20.8	12	4/5	49
31.2	12	4/5	73
41.7	12	4/5	98
62.5	12	4/5	146
125	12	4/5	293
250	12	4/5	583
500	12	4/5	1172

can use channels with a bandwidth of either 125 kHz, 250 kHz or 500 kHz, depending on the region or the frequency plan. The spreading factor is chosen by the end-device and influences the time it takes to transmit a frame.

3.3.1.4 LoRa frequency plan and data rate available for india

The frequency plan is specified in the LoRaWAN regional parameters document. here, we used AS923 (923 - 925 MHz) that consisting of 8 LoRa uplink channels, where frequency bands elements of [923.2, 923.4, . . . , 924.6 MHz]. All channels operated using an SF12 spreading factor and 125 kHz bandwidth that are supported in india as shown in Table 3.4. LoRa Modulation uses chirp spread spectrum for encoding the data in which each bit is spread by chipping factor. Small spreading factors offer high data rate and less OTA time.”RFU” refers to ”Reserved for Future Usage”.

Table 3.4: LoRa spreading factors and datarates

Data Rate	Configuration	Indicative Physical Bitrate [bits/sec]
0	LoRa: SF 12/125kHz	250
1	LoRa: SF 11/125kHz	440
2	LoRa: SF 10/125kHz	980
3	LoRa: SF 9/125kHz	1760
4	LoRa: SF 8/125kHz	3125
5	LoRa: SF 7/125kHz	5470
6	RFU	RFU
7	FSK: 50 Kbps	50000
8-14	RFU	
15	Defined in LoRaWAN	

3.4 Geometric Analysis for Determining Slant Distance (d) to Satellite

Communication via satellite begins when the satellite is positioned in the desired orbital position. Ground stations can communicate with satellites only when the satellite is in their visibility region.

The basic geometry between a GEO satellite and ground station is depicted in Figure 3.3.

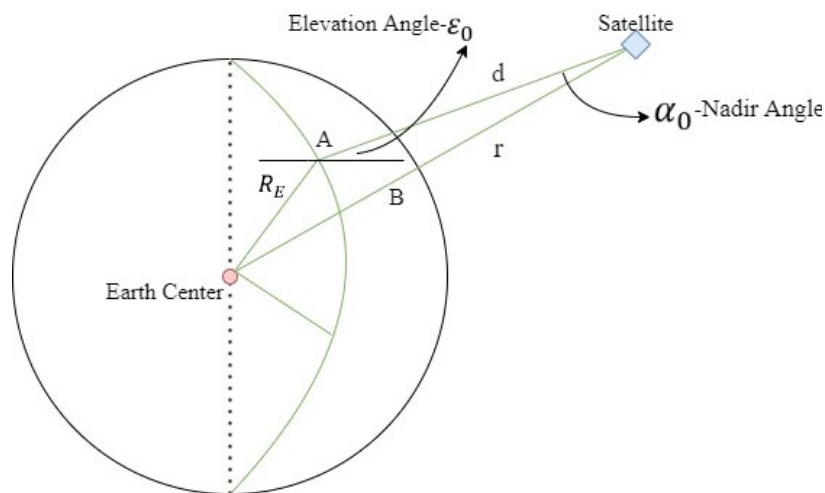


Figure 3.3: Geometry of ground station

The ground station (A) and satellite (SAT) are indicated by the first two points, while the Earth's centre is indicated by the third. B stands for the subsatellite point, which is where the Earth's surface and the joining line between the satellite and the

planet's centre intersect. The slant range between a satellite and a ground station is represented by distance (d). This range fluctuates over time because, in the case of LEO satellites, because they fly too quickly above terrestrial stations. In Fig. 3.3, the orbital radius r is:

$$r = R_E + H \quad (1)$$

$R_E = 6378$ km is Earth's radius and H is satellite's altitude. The angle formed between ideal horizon plane and the slant range is elevation angle. The triangle from Fig. 3.3 drawn separately on a plane leads to Fig. 3.4 [17].

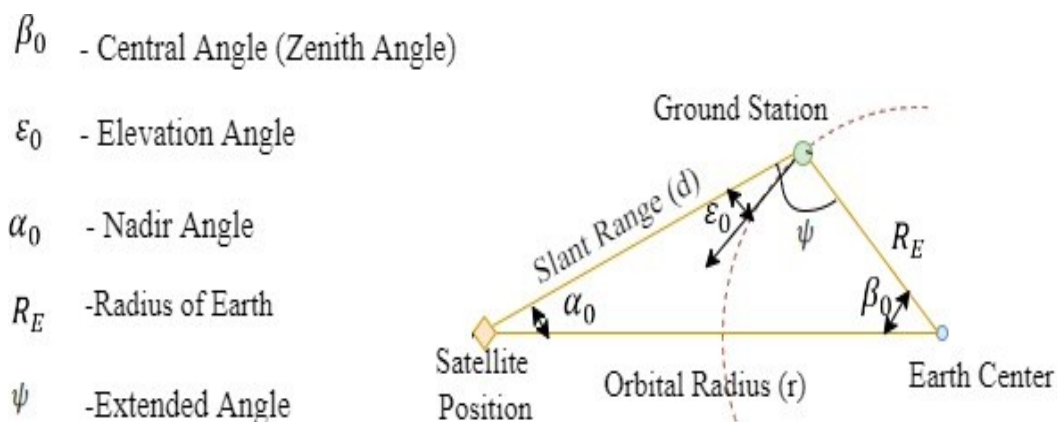


Figure 3.4: Detailed geometric overview

Two sides of this triangle are usually known (the distance from the ground station to the Earth's center $R_E = 6378$ km, and distance from the satellite to Earth's center-orbital radius). The angle under which the satellite sees the ground station is called nadir angle. There are four variables in this triangle: ε_0 - is elevation angle, α_0 - is nadir angle, β_0 - is central angle and d is slant range.

The most important parameter is the slant range d (distance from the ground station to the satellite). This parameter will be used during the link budget calculation, and it is expressed through elevation angle. By applying cosines law for triangle at Fig. 3.4 we will get as:

$$r^2 = R_E^2 + d^2 - 2R_E d \cos (90 + \varepsilon_0) \quad (2)$$

Solving the above equation by d , yields:

$$d = R_E \left[\sqrt{\left(\frac{r}{R_E}\right)^2 - \cos^2 \varepsilon_0 - \sin \varepsilon_0} \right] \quad (3)$$

Substituting, $r = H + R_E$ at Equation (3) finally we will get the slant range as function of elevation angle ε_0 :

$$d = R_E \left[\sqrt{\left(\frac{H + R_E}{R_E}\right)^2 - \cos^2 \varepsilon_0 - \sin \varepsilon_0} \right] \quad (4)$$

The range under the lowest elevation angle represents the worst link budget case, since that range represents the maximal possible distance between the ground station and the satellite. More power is required to overcome larger distance. Thus a trade off should be applied, in order to optimize the required transmit power and the designed horizon plane.

3.4.1 Free Space Path Loss (FSPL) and Receiver Sensitivity (S)

3.4.1.1 Free Space Path Loss

The free space path loss is used to predict the strength of a RF signal at a particular distance. The path loss in free space (dB) defines the loss during propagation from transmitter to receiver, it was calculated from [28]:

$$\text{FSPL} = 20 \log(d) + 20 \log(f) + 32.45 \quad (5)$$

where d was distance from earth station to satellite (km) and f was frequency band (MHz/GHz) for transmission.

3.4.1.2 Receiver Sensitivity

Receiving sensitivity is a very important parameter in the LoRa module. The sensitivity is in negative units. The smaller the negative value, the higher the receiving sensitivity. Sensitivity is a function that is effective when the LoRa module receives data, so sensitivity is generally called receiving sensitivity.

In the LoRa module, we use the SX1276 transmitter which has a 6dB noise figure, NF [29]. The receiver sensitivity, is the minimum signal level required at the receiver to achieve a target performance, depending on bandwidth. It is calculated from [30]:

$$S = -174 + 10 \log(BW) + NF + \text{SNR}_{\text{limit}} \quad (6)$$

where BW is the bandwidth (Hz) and $\text{SNR}_{\text{limit}}$ is the limiting Signal to Noise Ratio (dB) (which has a lower value when communicating with higher spreading factor). SF12 (i.e., Spreading Factor = 12) and $\text{SNR}_{\text{limit}} = -20$ dB are taken for evaluation.

Chapter 4

Methodology for Link Budget Calculation

A link budget is the term used that accounts for the power received at the receiver. This accounts for all of the gain and losses from the transmitter to the point at which it is received by the receiver. It includes losses from cables/fibers and other components in the Tx/Rx chain, gains from the antenna, amplifiers etc. and propagation loss when travelling through air or another medium. The link budget is an important value that enables engineers to design systems based on the required sensitivity of a receiver at a particular distance. It is a way of quantifying the link performance.

4.1 Modelling of Link Budget- Received Power Calculation

The feasibility of successful communication between transmitter and receiver, requires that signal power at the receiver power was greater than or equal to the receiver sensitivity, the difference is called the link margin. Ignoring losses from environmental factors (e.g., rain, temperature, etc.) received power can be calculated from [31]:

$$\text{Receiver power} = \text{Tx power} - \text{Tx Connection loss} + \text{Tx Antenna gain} + \text{Rx Antenna gain} - \text{Rx Connection loss} - \text{FSPL} \quad (7)$$

where Tx is transmitter, Rx is receiver, connection loss (dB) was the loss between device and antenna connection and antenna gain (dBi) was the value that increase signal power of device.

Chapter 5

Performance Evaluation

The Mathematically modelled and software simulated results for the proposed Link Budget Model employing AS 923 MHz and 2.412 GHz channel are shown in this section.

5.1 Mathematically Modelled and Software Simulated Results for AS 923 MHz and 2.412 GHz Channels

5.1.0.1 Mathematical Link Budget Model 923.2 MHz Transmitting Channel - (Channel 1) for an Orbital Altitude of 6978 Km

Modelling is done for finding the maximum distance up to which the signal can cover while transmitting from IoT device by considering certain factors at the transmitting node such as transmitting power of 20 dBm, connection loss 1 dB, antenna gain 2 dBi, transmitting in channel 1 with SF of 12 and 125 kHz bandwidth and by ignoring loss from environment factors. The same constraints are chosen at the receiving end along with receiver sensitivity of -137dBm and SNR_{limit} of -20 dB. Mathematically modelled FSPL values for several elevation angles, ranging from $[90^\circ, 80^\circ, \dots, 0^\circ]$, are shown in table 5.1. When orbital height becomes 600 km, (EL = 90°) we will get maximum link margin 11.681 dB, when the signal propagates from 1075

Table 5.1: FSPL values

Elevation Angle (EL) (Degree)	Extended Angle (Degree)	Zeinth Angle	Distance (Km)	FSPL (dB)
90	180	0	600	147.3189
80	170	0.866	608.47	147.52
70	160	1.78	634.71	147.89
60	150	2.80	683.2	148.53
50	140	4.01	760.62	149.46
40	130	5.55	881.9	150.74
30	120	7.66	1075.53	152.47
20	110	10.80	1391.49	154.57
10	100	15.81	1930.97	157.55
0	90	19.94	2829.8	160.06

Km to 1930 Km (EL= 30°, 10°) and the link margin makes a transition from 6.53 to 2.54 dB as shown in Fig. 5.1, 5.2, 5.3 respectively.

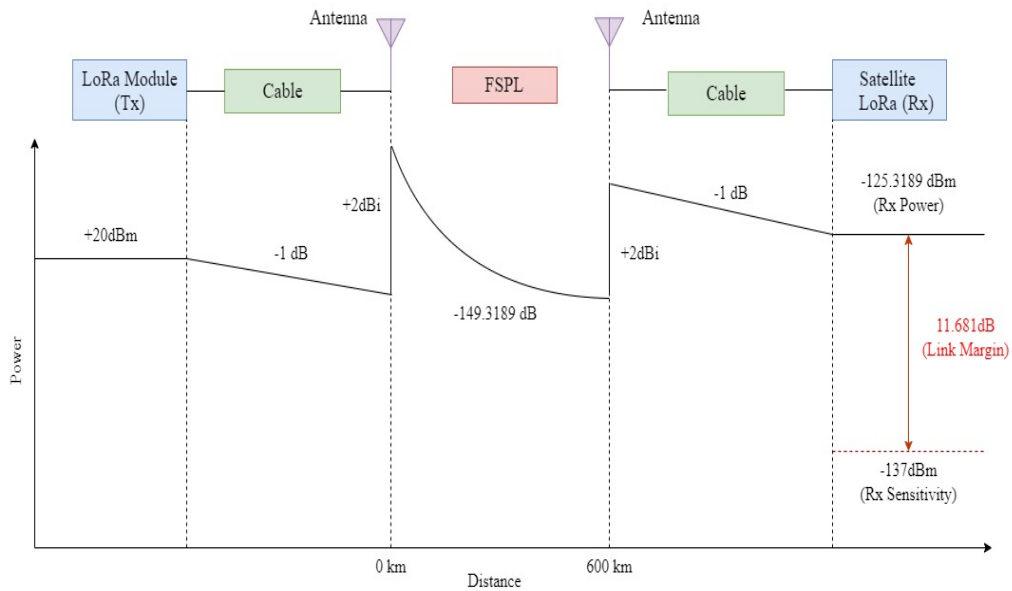


Figure 5.1: Link margin at a distance of 600 Km

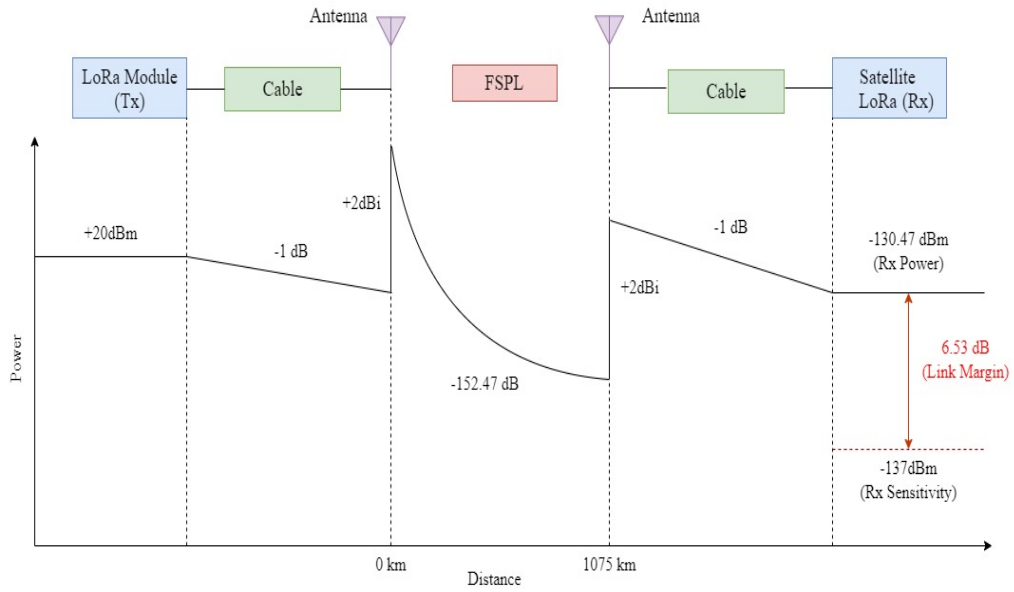


Figure 5.2: Link margin at a distance of 1075 Km

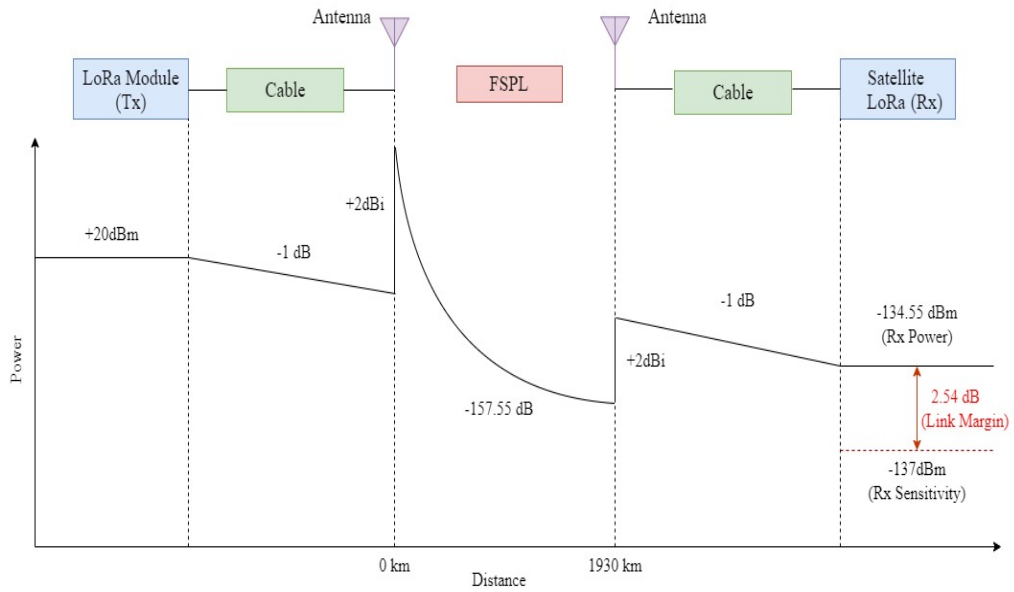


Figure 5.3: Link margin at a distance of 1930 Km

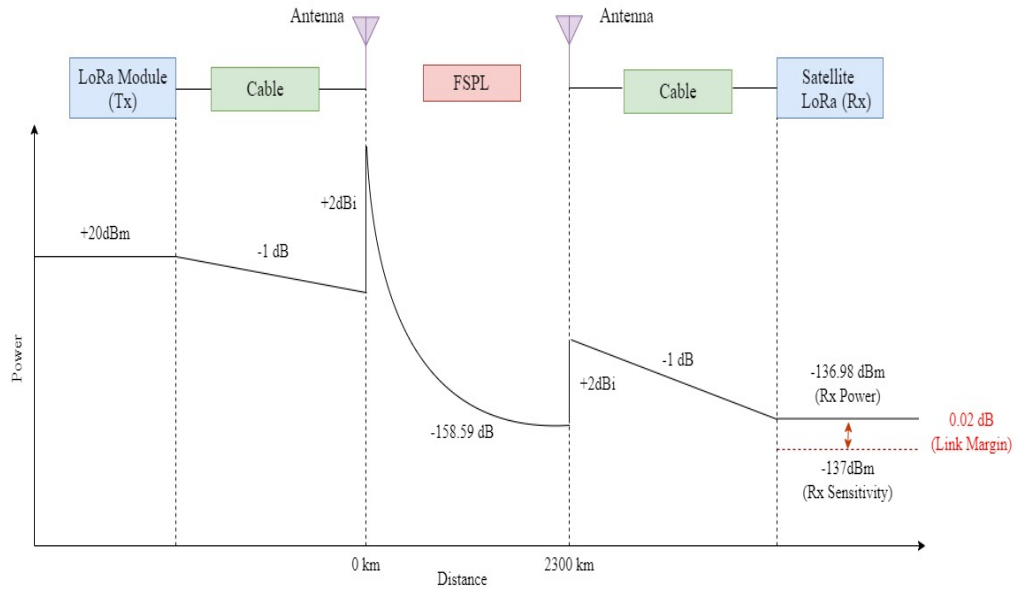


Figure 5.4: Link margin at a distance of 2300 Km

The maximum distance that can be transmitted was 2300 km while with 20 dBm power (minimum EL = 5.2895°), with received power -136.98 dBm that is close to sensitivity and link margin closer to 0 dB as shown in Fig. 5.4. The maximum threshold level of distance up to which the signal can be transmitted for different orbital altitudes are shown in table 5.2

Table 5.2: Threshold levels of distances for different orbital altitudes

Orbital Altitude [Km]	H	H	H	H	H	H	H
	6978Km	7078Km	7178Km	7278Km	7378Km	7478Km	7578Km
Max.El	Range [Km]	Range [Km]	Range [Km]	Range [Km]	Range [Km]	Range [Km]	Range [Km]
0	2830	3065	3289	3504	3708	3900	4048
10	1942	2180	2372	2577	2770	2955	3136
20	1386	1581	1765	1947	2120	2287	2453
30	1070	1234	1392	1549	1701	1849	1996
40	886	1027	1164	1302	1436	1567	1698
50	758	883	1005	1128	1248	1366	1486
60	683	794	905	1018	1129	1238	1348
70	634	742	847	954	1058	1160	1266
80	608	707	809	908	1012	1113	1214
90	600	700	800	900	1000	1100	1200

5.1.0.2 Software Validated Results for AS 923 MHz

Mathematically modelled results are validated by using Satellite simulation softwares. Satellite Tool Kit (STK) is a suit of software that allows engineers and scientists to design and develop complex dynamic simulations of real-world problems. Their common fields of use includes space exploration, geospacial intelligence, spacecraft mission design, missile defense, spacecraft operations.

For verification and validation a scenario is generated by choosing a particular latitude and longitudinal coordinates for an satellite orbital altitude of 6978 Km as represented in Fig. 5.5.

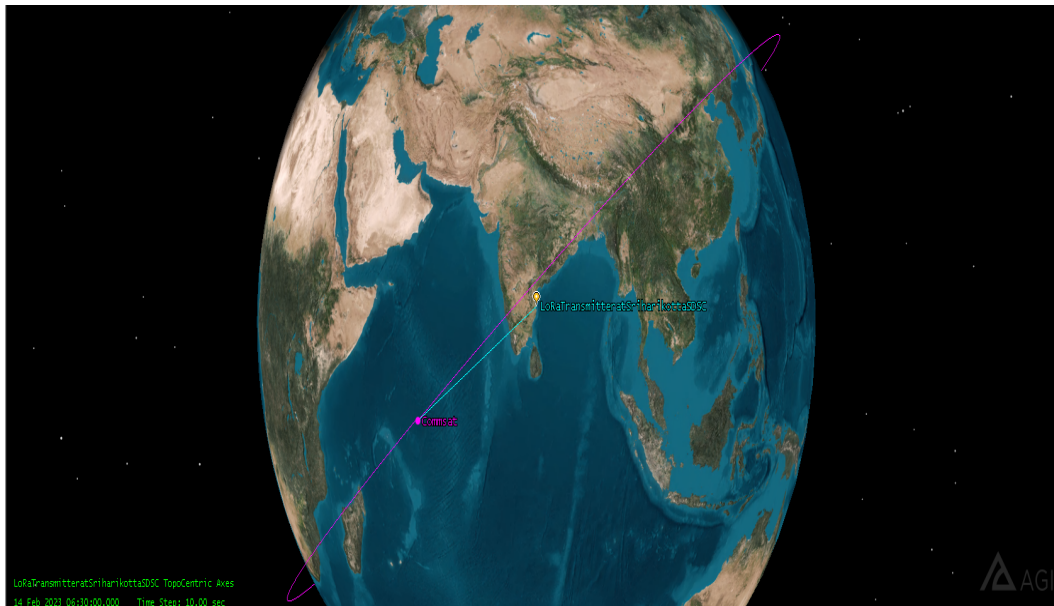


Figure 5.5: Generated scenario

2D plot for the generated scenario is represented in Fig. 5.6. While simulating the scenario the minimum and maximum duration of access times to satellite is came out to be 1.2 Minute and 12.9 Minutes respectively as indicated in Fig. 5.7.

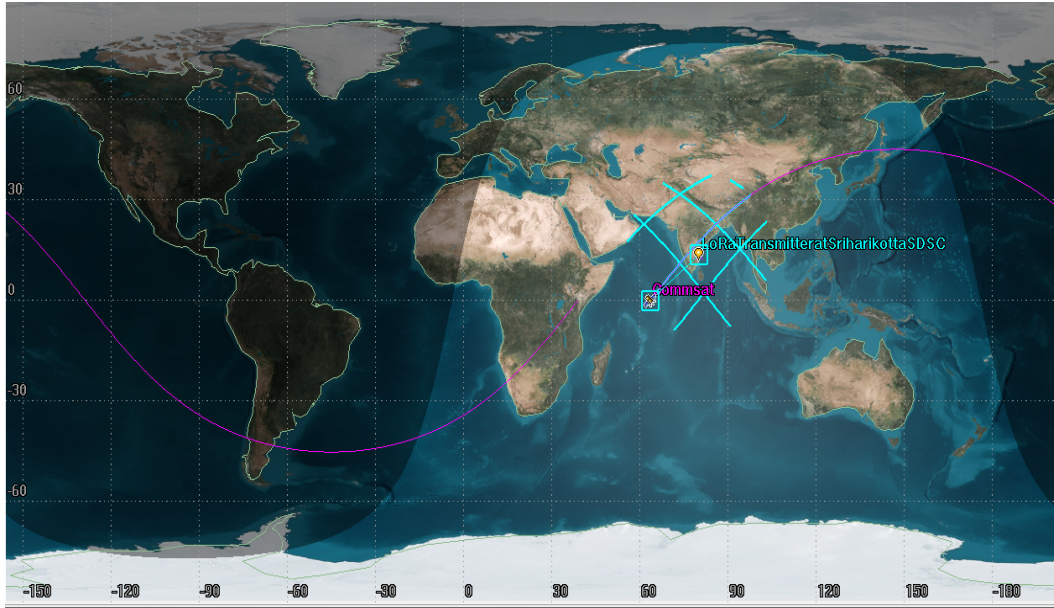


Figure 5.6: 2D Plot

Civil Air Patrol Use Only
 Place-LoRaTransmitteratSriharikotaSDSC-Transmitter-Transmitter2-To-Satellite-Commsat-Receiver-Receiver1: Access Summary Report

Transmitter2-To-Receiver1

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	14 Feb 2023 06:30:00.000	14 Feb 2023 06:42:43.776	763.776
2	14 Feb 2023 08:13:19.729	14 Feb 2023 08:22:24.504	544.775
3	14 Feb 2023 13:29:35.996	14 Feb 2023 13:30:50.908	74.912
4	14 Feb 2023 15:06:33.625	14 Feb 2023 15:18:51.508	737.882
5	14 Feb 2023 16:47:33.870	14 Feb 2023 17:00:33.451	779.581
6	15 Feb 2023 04:58:27.914	15 Feb 2023 05:11:02.025	754.111

Global Statistics

Min Duration	3	14 Feb 2023 13:29:35.996	14 Feb 2023 13:30:50.908	74.912
Max Duration	5	14 Feb 2023 16:47:33.870	14 Feb 2023 17:00:33.451	779.581
Mean Duration				609.173
Total Duration				3655.037

Figure 5.7: Access time report

While analysing Azimuth, Elevation angle and Range (AER) graph Fig. 5.8 the maximum distance from IoT device to satellite is came out to be 2830 Km which represents 100 percent similitude between software simulated result and mathematical modelling.

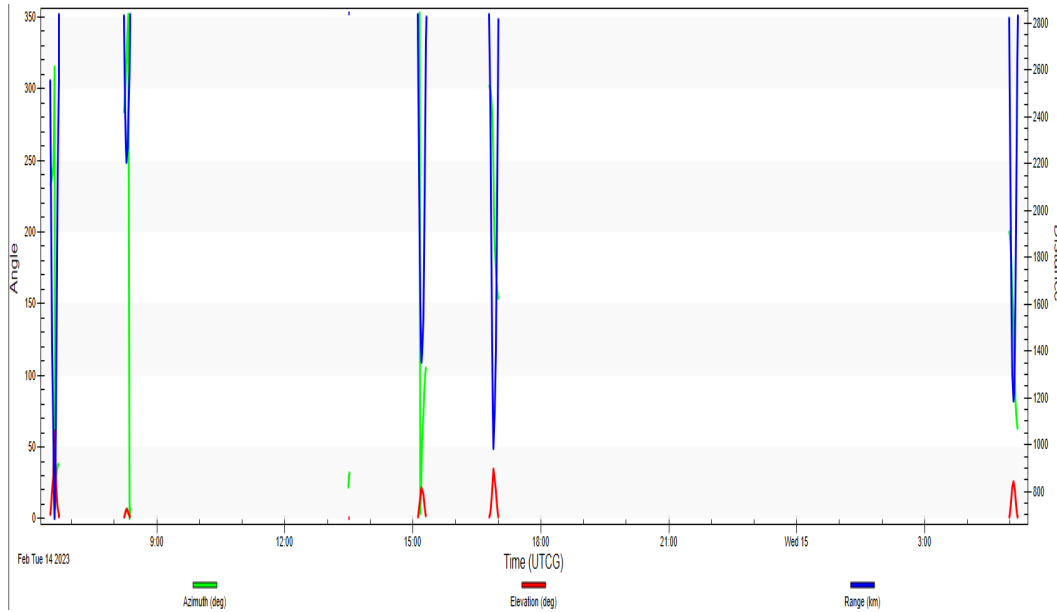


Figure 5.8: AER graphical view

The maximum Energy per bit to noise power spectral density and carrier to noise ratio during the link establishment is came out to be 20.10 dB and 40 dB as indicated in Fig. 5.9,5.10 represents the better signal quality over the distances that signal encounters.

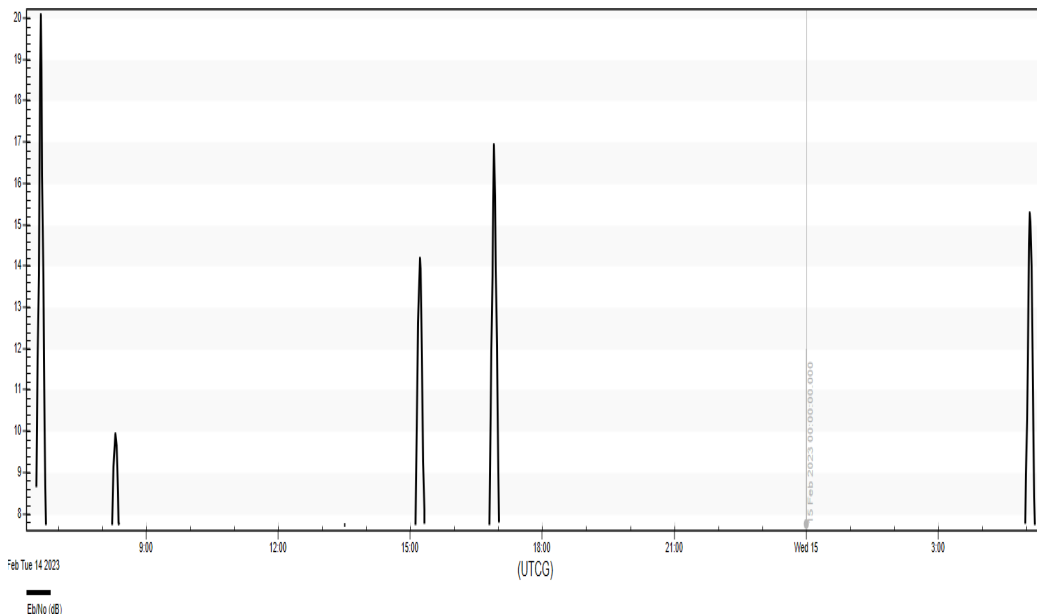


Figure 5.9: SNR Plot

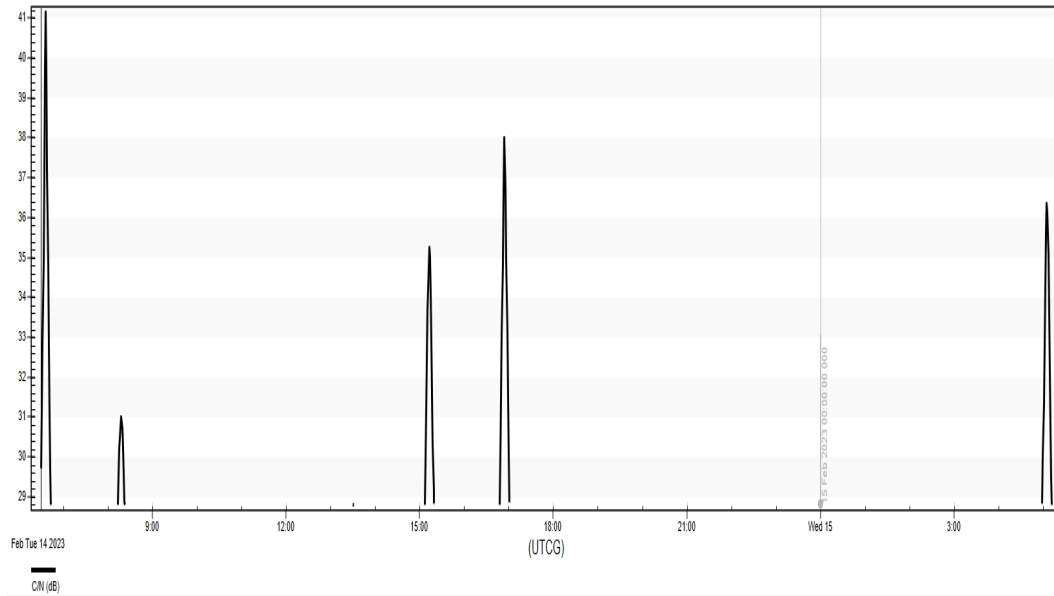


Figure 5.10: C/N Graph

Bit error rates are fairly good enough for establishment of link as illustrated in Fig. 5.11. Link budget report generated Fig. 5.12 evidently implies the effectiveness of direct access to satellites by IoT devices with AS 923 MHz channel.

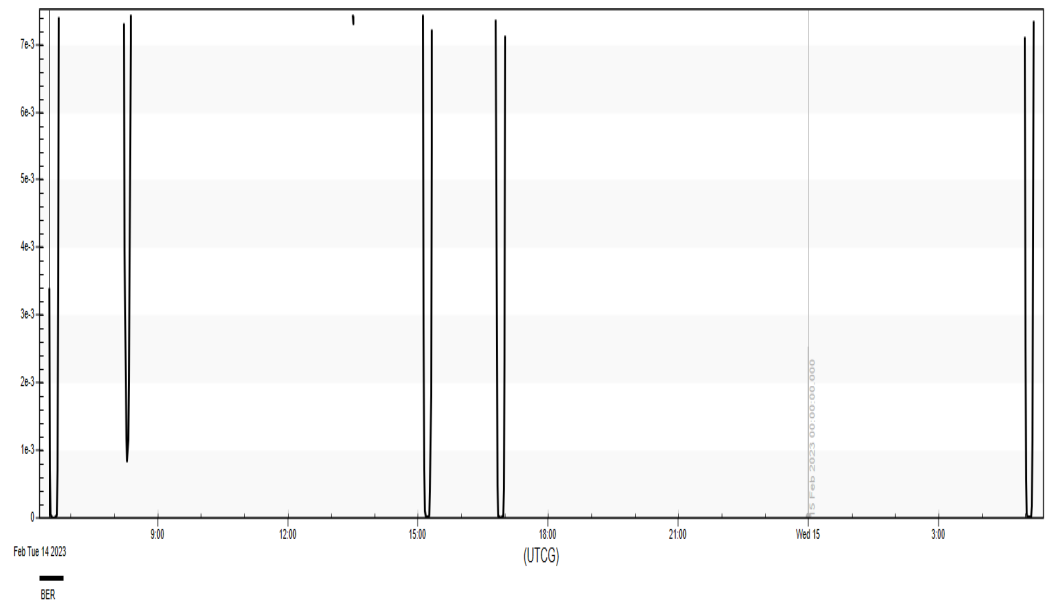


Figure 5.11: BER Plot

7 Feb 2023 23:10:17

Transmitter-Transmitter2-To-Satellite-COMSAT-Receiver-Receiver3: Link Budget - Short Form

Rcvd. Frequency (GHz)	Rcvd. Iso. Power (dBW)	Flux Density (dBW/m ²)	g/T (dB/K)	C/No (dB*Hz)	Bandwidth (kHz)	C/N (dB)	Eb/No (dB)	BER
0.925021	-167.229	-146.450191	20.000000	81.370429	125.000	30.4013	11.3704	1.066481e-04
0.925021	-165.607	-144.828351	20.000000	82.992269	125.000	32.0232	12.9923	4.043608e-06
0.925020	-163.638	-142.859837	20.000000	84.960783	125.000	33.9917	14.9608	1.083691e-08
0.925019	-161.180	-140.401282	20.000000	87.419338	125.000	36.4502	17.4193	5.445307e-14
0.925017	-158.084	-137.305781	20.000000	90.514838	125.000	39.5457	20.5148	1.329487e-26
0.925008	-154.876	-134.097845	20.000000	93.722775	125.000	42.7537	23.7228	1.000000e-30
0.924992	-154.850	-134.071382	20.000000	93.749238	125.000	42.7801	23.7492	1.000000e-30
0.924984	-158.046	-137.267222	20.000000	90.553398	125.000	39.5843	20.5534	8.012388e-27
0.924981	-161.147	-140.368804	20.000000	87.451816	125.000	36.4827	17.4518	4.410398e-14
0.924980	-163.611	-142.832829	20.000000	84.987790	125.000	34.0187	14.9878	9.798935e-09
0.924979	-165.583	-144.804963	20.000000	83.015657	125.000	32.0466	13.0157	3.822445e-06
0.924979	-167.208	-146.429120	20.000000	81.391499	125.000	30.4224	11.3915	1.029286e-04
0.924979	-168.019	-147.240858	20.000000	80.579762	125.000	29.6107	10.5798	3.616970e-04

Rcvd. Frequency (GHz)	Rcvd. Iso. Power (dBW)	Flux Density (dBW/m ²)	g/T (dB/K)	C/No (dB*Hz)	Bandwidth (kHz)	C/N (dB)	Eb/No (dB)	BER
0.925013	-168.001	-147.222833	20.000000	80.597787	125.000	29.6287	10.5978	3.525628e-04
0.925011	-167.177	-146.398017	20.000000	81.422603	125.000	30.4535	11.4226	9.764482e-05

Figure 5.12: Link budget summary report

Thus a reliable communication link establishment is possible via 923.2 MHz channel with 20 dBm transmitting power for an orbital altitude of 6978 Km.

5.2 Impact of Low power Transmission

Mathematically modelled FSPL values for several elevation angles, ranging from [90°, 80°, ..., 0°], are shown in table 5.3 and its graphical representation are shown in Fig. 5.13 while using 2.412 GHz channel with 20dBm transmitting power. At 35000Km the received power falls below the sensitivity which results in a negative link margin as shown in Fig. 5.14. So it is impossible to reach up to the orbital altitude of GEO with this power.

Table 5.3: FSPL values for GEO satellite use case

Elevation Angle (EL) (Degree)	Extended Angle (Degree)	Zeinth Angle	Distance (Km)	FSPL (dB)
90	180	1.416	35000	182.63
80	170	1.4163	35082.07	182.65
70	160	1.4187	35327.09	182.71
60	150	1.4207	35371.41	182.81
50	140	1.4231	36288.57	182.95
40	130	1.4259	36988.83	183.11
30	120	1.4392	37818.67	183.31
20	110	1.4322	38760.24	183.52
10	100	1.4359	39790.96	183.75
0	90	1.4285	40883.49	183.98

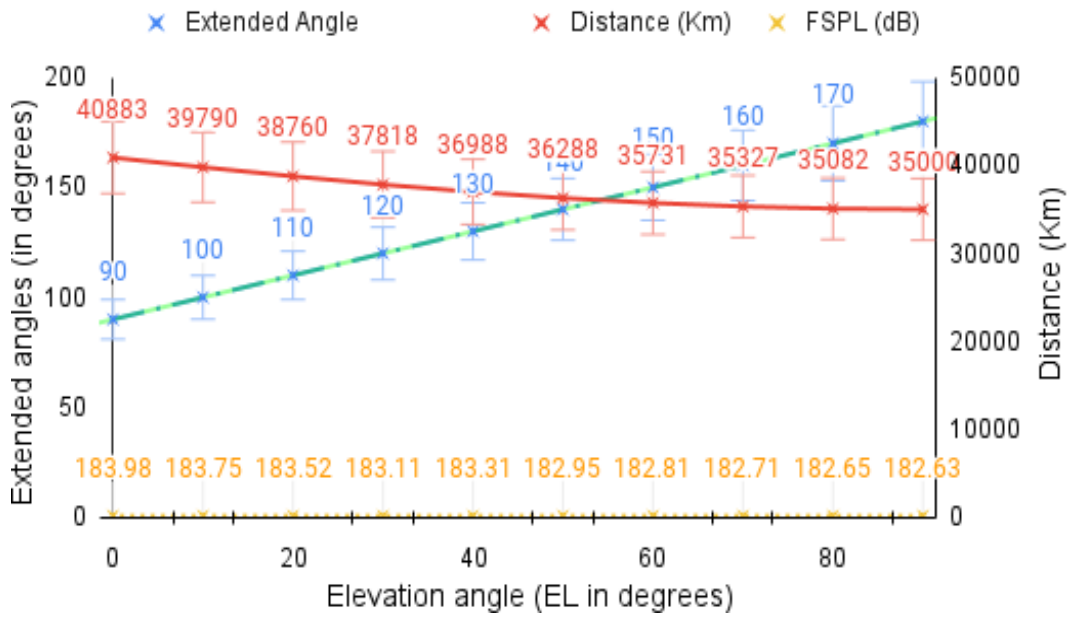


Figure 5.13: Combined graphical view

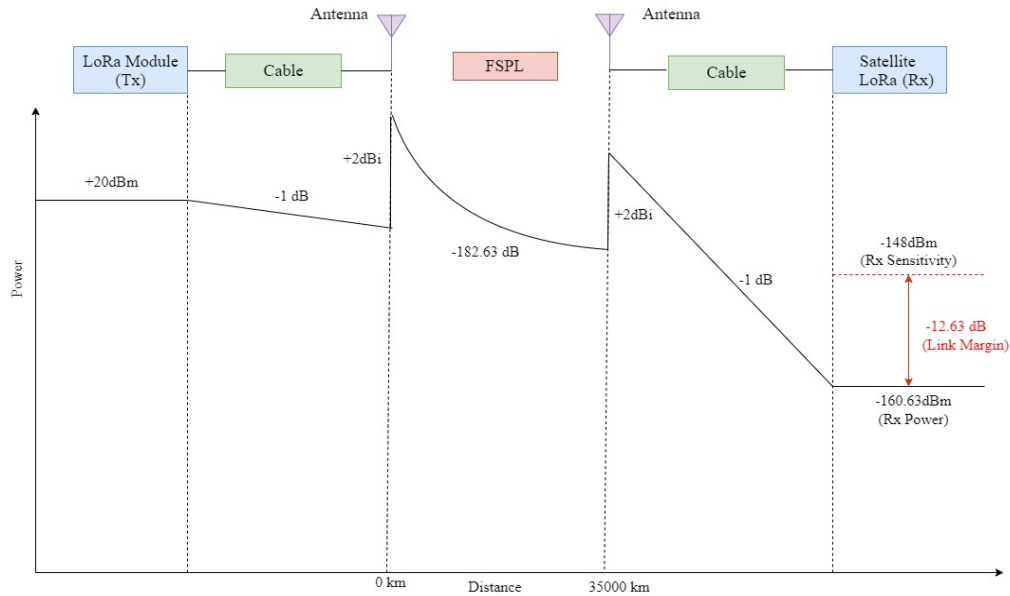


Figure 5.14: Link margin at a distance of 35000 Km

5.3 LoRa Range Determining Parameters and it's Relevance

Basic factors that can be used to describe a network in a radio technology are :

- Range
- Data Transfer Speed
- Energy Consumption

LoRa Range Optimization Strategies For GEO Satellites are :

- **Antenna choice (Gain, Height):** Antenna heights and gains can significantly increase a communication system's range. One of the most affordable methods to improve a system is to increase antenna performance. However, regulatory requirements or practical factors may occasionally place a limit on antenna gains.
- **Transmission Power (Pc1-Pc5, Class A-C):** The more transmit power a device radiates the further away it can be received. In the real world, you must increase power by 4-10 times to double the communication range. Sometimes even a 20 times increase is needed to double the range.

- **Frequency of System (C, X, ...W Bands):** Lower frequency bands are less attenuated resulting in better reception of signal quality with good SNR
- **Receiver Sensitivity:** Compared to a bad receiver, one with strong receive sensitivity can detect a signal from a much greater distance. The communication range will be significantly extended by a receiver that is 4 times (6dB) more sensitive than another receiver. A 6dB increase in receive sensitivity is equivalent to a 4X increase in transmission power. However, a receiver that is 6 dB better will use relatively little extra power. Using a more sensitive receiver rather than a more powerful transmitter is always preferable, more cost-effective, and more effective.
- **Elevation Angles:** IoT devices with very low elevation angles are thought to operate exceedingly poorly via radio links due to significant path loss. Therefore, in such circumstances, the probability of effective transmission is low. IoT devices can either be programmed to stop broadcasting when the satellite is at or below the threshold elevation angle, or the satellite's beam width can be adjusted and there by frame repetitions can be avoided [9].
- **Energy per bit:** The energy per bit (E_b/N_0) is the transmit power divided by the over-the-air data rate. Reducing the data rate in half will provide you the same range improvement as doubling your power or doubling your receive sensitivity. Slow data rate radios go much farther than fast radios.

5.4 Results and Discussion

5.4.1 2.412 GHz Transmitting Channel - (Channel 1) for Direct Access to GEO Satellites

In the 2.4 GHz band, 1-(2.412 GHz), 6, and 11 are the only non-overlapping channels. Selecting one or more of these channels is an important part of setting up the network correctly and choosing proper modulation schemes, transmitting power

(Power class-1 devices), antenna gain, spreading factor, sensitivity are necessarily important for establishing communication link with far bodies.

A system is modelled in which the transmitting node transmits at 35dBm power, Helical spring antenna with gain of 12.8dBi and with a spreading factor of 12, on a spreading bandwidth of 10KHz with proper modulation and coding schemes resulting in a sensitivity of -148 dBm that can provide a datarate up to 0.024 Kb/sec.

2D plot for the generated scenario is represented in Fig. 5.15. While simulating the scenario duration of access times to satellite is came out to be 24 hrs as indicated in Fig. 5.16.

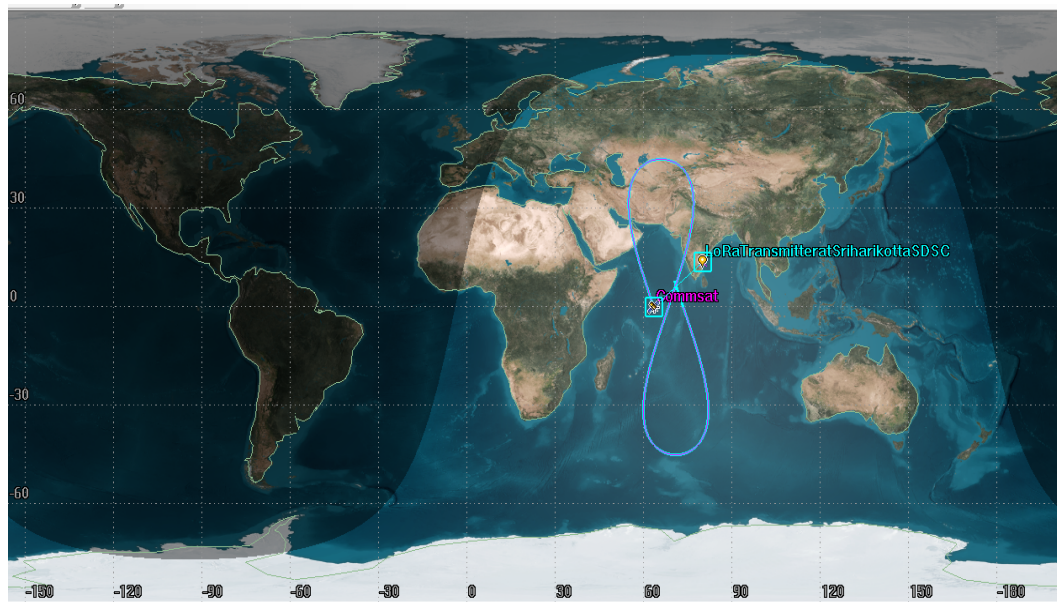


Figure 5.15: 2D Plot

Transmitter2-To-Receiver1

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	14 Feb 2023 06:30:00.000	15 Feb 2023 06:30:00.000	86400.000

Global Statistics

Min Duration	1	14 Feb 2023 06:30:00.000	15 Feb 2023 06:30:00.000	86400.000
Max Duration	1	14 Feb 2023 06:30:00.000	15 Feb 2023 06:30:00.000	86400.000
Mean Duration				86400.000
Total Duration				86400.000

Figure 5.16: Access time report

While analysing Azimuth, Elevation angle and Range (AER) graph Fig. 5.17 the maximum distance from IoT device to satellite is came out to be 40883 Km at zero degree elevation which represents 100 percent similarity between software simulated result and mathematical modelling.

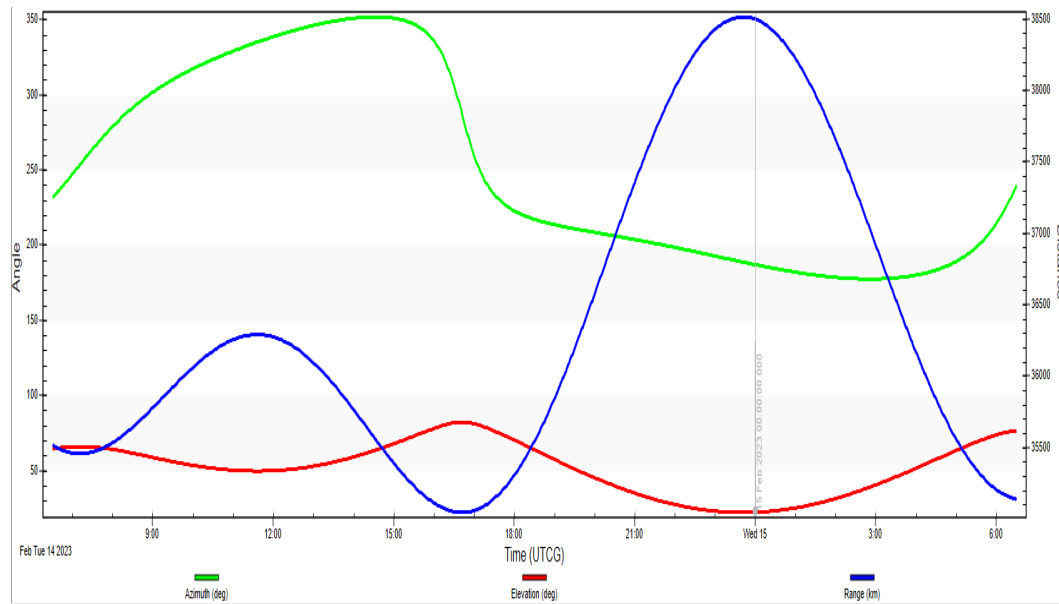


Figure 5.17: AER graphical view

The maximum Energy per bit to noise power spectral density is came out to be 10 dB which is quite good for establishing a communication link with this low

transmitting power and it will become negative at low elevation angle due to lack of line of sight resulting in high FSPL as represented in Fig. 5.18.

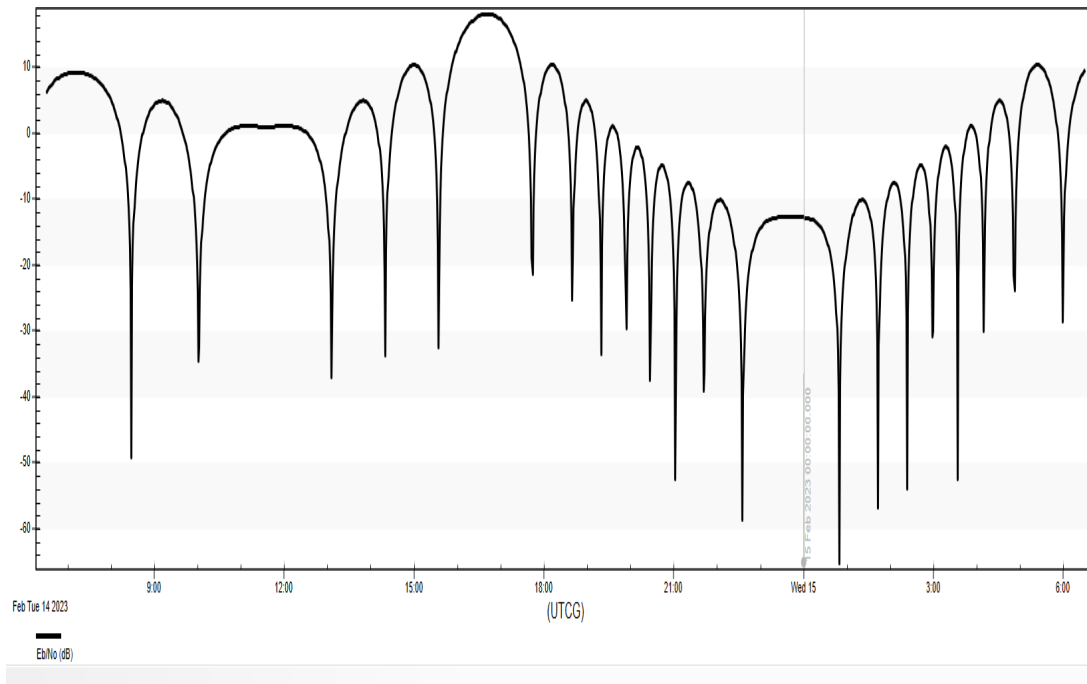


Figure 5.18: SNR Plot

Bit error rates are acceptable establishment of link transmitting at 35 dBm as illustrated in Fig. 5.19. Link budget report generated Fig. 5.20 clearly emphasis the capacity of PC1 device to enable direct access to satellites by IoT devices with 2.412 GHz channel.

Time (UTC)	g/T (dB/K)	Eb/No (dB)	BER
14 Feb 2023 06:30:00.000	20.00000000	6.13969982	2.12998949e-02
14 Feb 2023 06:31:00.000	20.00000000	6.35711760	1.88083669e-02
14 Feb 2023 06:32:00.000	20.00000000	6.56152966	1.66472495e-02
14 Feb 2023 06:33:00.000	20.00000000	6.75378547	1.47719373e-02
14 Feb 2023 06:34:00.000	20.00000000	6.93465816	1.31435784e-02
14 Feb 2023 06:35:00.000	20.00000000	7.10485388	1.17284401e-02
14 Feb 2023 06:36:00.000	20.00000000	7.26501974	1.04973239e-02
14 Feb 2023 06:37:00.000	20.00000000	7.41575056	9.42501388e-03
14 Feb 2023 06:38:00.000	20.00000000	7.55759460	8.48977738e-03
14 Feb 2023 06:39:00.000	20.00000000	7.69105851	7.67290650e-03
14 Feb 2023 06:40:00.000	20.00000000	7.81661155	6.95831801e-03
14 Feb 2023 06:41:00.000	20.00000000	7.93468924	6.33219455e-03
14 Feb 2023 06:42:00.000	20.00000000	8.04569655	5.78267068e-03
14 Feb 2023 06:43:00.000	20.00000000	8.15001065	5.29955882e-03
14 Feb 2023 06:44:00.000	20.00000000	8.24798328	4.87411094e-03
14 Feb 2023 06:45:00.000	20.00000000	8.33994290	4.49881450e-03
14 Feb 2023 06:46:00.000	20.00000000	8.42619650	4.16721272e-03
14 Feb 2023 06:47:00.000	20.00000000	8.50703120	3.87375411e-03
14 Feb 2023 06:48:00.000	20.00000000	8.58271573	3.61366166e-03
14 Feb 2023 06:49:00.000	20.00000000	8.65350163	3.38282117e-03
14 Feb 2023 06:50:00.000	20.00000000	8.71962437	3.17768602e-03
14 Feb 2023 06:51:00.000	20.00000000	8.78130437	2.99519588e-03

Figure 5.19: Short link budget report

Transmitter-Transmitter2-To-Satellite-Commsat-Receiver-Receiver1: Link Budget - Short Form

Rcvd. Frequency (GHz)	Rcvd. Iso. Power (dBW)	Flux Density (dBW/m ²)	g/T (dB/K)	C/No (dB*Hz)	Bandwidth (kHz)	C/N (dB)	Eb/No (dB)	BER
2.412000	-170.418	-141.315009	20.000000	78.180900	10.000	38.1809	6.1397	2.129989e-02
2.412000	-170.201	-141.097591	20.000000	78.398317	10.000	38.3983	6.3571	1.880837e-02
2.412000	-169.996	-140.893179	20.000000	78.602729	10.000	38.6027	6.5615	1.664725e-02
2.412000	-169.804	-140.700923	20.000000	78.794985	10.000	38.7950	6.7538	1.477194e-02
2.412000	-169.623	-140.520050	20.000000	78.975858	10.000	38.9759	6.9347	1.314358e-02
2.412000	-169.453	-140.349855	20.000000	79.146054	10.000	39.1461	7.1049	1.172844e-02
2.412000	-169.293	-140.189689	20.000000	79.306220	10.000	39.3062	7.2650	1.049732e-02
2.412000	-169.142	-140.038958	20.000000	79.456950	10.000	39.4570	7.4158	9.425014e-03
2.412000	-169.000	-139.897114	20.000000	79.598794	10.000	39.5988	7.5576	8.489777e-03
2.412000	-168.867	-139.763650	20.000000	79.732258	10.000	39.7323	7.6911	7.672907e-03
2.412000	-168.741	-139.638097	20.000000	79.857811	10.000	39.8578	7.8166	6.958318e-03
2.412000	-168.623	-139.520019	20.000000	79.975889	10.000	39.9759	7.9347	6.332195e-03
2.412000	-168.512	-139.409012	20.000000	80.086896	10.000	40.0869	8.0457	5.782671e-03
2.412000	-168.408	-139.304698	20.000000	80.191210	10.000	40.1912	8.1500	5.299559e-03
2.412000	-168.310	-139.206725	20.000000	80.289183	10.000	40.2892	8.2480	4.874111e-03
2.412000	-168.218	-139.114765	20.000000	80.381143	10.000	40.3811	8.3399	4.498815e-03
2.412000	-168.132	-139.028512	20.000000	80.467396	10.000	40.4674	8.4262	4.167213e-03
2.412000	-168.051	-138.947677	20.000000	80.548231	10.000	40.5482	8.5070	3.873754e-03

Figure 5.20: Link budget report

Thus a reliable communication link establishment is possible via 2.412 GHz channel with 35dBm transmitting power for GEO stationary orbital altitude.

Chapter 6

Advantages

- **Greater device support, improved coverage, and energy-efficient operation:** Support for large number of devices can be made possible with LoRa by utilising SF of 12 in order to cover a longer distance. Hence we are using low power for transmission energy is not getting wasted
- **Diverse service related capabilities:** Direct access to GEO satellite by IoT device can provide diverse service related capabilities that provide supports in different application level scenarios like smart agriculture, environmental monitoring, disaster management etc...
- **Better acquisition of signal in the presence of noises:** LoRa signals can demodulated effectively in presence of noise since they are using different spreading factors that provide high level of immunity against noise and by using unique codewords for different transmitters, each one of which can transmit simultaneously.
- **Group Based Communication to decrease the signalling overhead and communication load at core network segments:** By employing a central station that can transmit data to GEO satellite will significantly reduce the signalling overhead and communication load to the satellite and leads to efficient use of satellite resources.

Chapter 7

Future Scope

- Studies are inevitable to determine the maximum number of sensors that can be integrated to the concept of IoT (Performing the scalability analysis) in terms of Spreading Factor, Packet payload size, No. of Nodes, Duty cycle parameters.
- Implementation of mechanisms that ensures least packet retransmission while allocating same spreading factor along with Proper Interference Mitigation Methods for Co channel-SF interference, Inter-SF interferences.
- Environmental factors such as temperature, humidity, rain attenuation, Spoilage and vegetation affecting LoRa performance are to be studied further.
- To realise a Software Defined Radio (SDR) based GEO satellite data transmitter and receiver pair by implementing LoRa on a SDR with appropriate change in the physical layer.

Chapter 8

Conclusion

Reliability in a link depends on different factors that combined together to provide efficient communication pathways.. From the evaluation done on distance communication and link budget model, it was shown that it is feasible to Communicate with a satellite having orbital height up to 35000 km with low transmit power while operating S-band (2-4GHz) However, in actual use, there may be loss from environmental factors, e.g., rain or temperature. Some of these factors can be overcome by increasing transmission power, but this is generally limited by domestic communication constraints, or designing antennae with higher gain, developing better modulation and coding schemes, interference mitigation schemes, methods to reduce packet retransmission rates there by increasing probability of successful transmission etc...

APPENDIX

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