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Design of Low Earth Orbit Constellation Satellite

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Abstract: ***This research explores the Low Earth Orbit (LEO) satellite constellations, replicating the commercial OneWeb system. This work is divided into two key sections: Distance & Geometric Analysis and Link Performance Analysis. We start by designing a Walker - star network of 12 orbital planes featuring a dozen satellites orbiting 950 km above the Earth's surface. To enhance coverage and connectivity, we carefully adjust the constellation's phasing parameters in MATLAB. We set up links with the satellite network by fixing a ground station at RMIT University. After locating the satellites closest to the base terminal, we determine their distances and plot their azimuth and elevation values on Skyplot. In the second phase, a thorough link budget analysis is conducted, including a comparison of modulation techniques 4PSK and 16QAM. The purpose is to find the best method for terminal use out of the two modulation schemes.***

Keywords: Walker - Star network, Budget analysis, Modulation techniques (4PSK, 16QAM)

1. Introduction

The emergence of Low Earth Orbit (LEO) satellite networks transformed worldwide communication and data delivery. [1] These constellations are made up of many small satellites that orbit the Earth at lower altitudes (when compared with typical GEO satellites, these operate between 160 and 2, 000 km above the Earth's surface.), creating benefits such as less latency and more range as compared to typical geostationary satellites. [2] OneWeb is a notable example of a commercial player in this domain due to its vast LEO satellite network. To obtain information about the actual layout and functioning of such networks, this project attempts to reproduce and study a reduced constellation of LEO satellites, identical to the OneWeb system.

Justification for Researching the Topic:

a) Significance to the Modern World: As LEO satellite networks such as OneWeb are being used for a wider range of programs, developers, researchers, and enterprises require a broad knowledge of their architecture and operation. This research project is an attempt to effectively explore the key factors and constraints related to these constellations.

b) Link Analysis: Aimed to provide a glimpse into the complexity of satellite communication systems, the project simulates a Walker - star constellation and evaluates the connectivity between the ground station and satellites. This information is crucial for ensuring uninterrupted connectivity and effective transfer of data, either for internet connectivity in remote regions or transfer of data in emergency cases.

c) Assessment of modulation: Determining the ideal modulation technique needs a comparison of different modulation schemes, namely 4PSK and 16QAM, in a set of LEO constellations. The efficacy and reliability of ways to communicate are greatly affected by this selection.

Key Findings and Additional Highlights:

- ***Duplicating a LEO Constellation identical to OneWeb:*** A practical and broad simulation of a constellation of low - Earth orbit satellites is developed, replicating the attributes of the OneWeb corporate network. This allows us to examine the constellation's effectiveness and conduct in a controlled setting.
- ***Phasing Parameter Optimization***: The constellation's phasing values are specifically selected for this evaluation. A key aspect of the project is to optimize these variables for optimum coverage and connectivity.
- ***Link Budget Analysis:*** A detailed link budget evaluation is done, using all factors including modulation strategies, transmit power, antenna gains, and losses. The accuracy and stability of the link between the satellites and the ground station can be determined with the help of this research.
- ***Modulation Scheme Analysis:*** Comparing the 4PSK and 16QAM modulation strategies, offers which one is best for interface utilization, which has a major effect on the standard of data distribution.

Essentially, this study simulates an actual constellation of low - Earth orbit satellites and offers a thorough performance analysis of it, highlighting modulation schemes and link budgets. In the end, this research enhances the field of satellite technology and its possible uses by offering an awareness of limitations and possibilities in low - Earth orbit (LEO) satellite communication.

2. Literature Review

Satellite communications have expanded substantially in recent times, owing to advances in technology, rising internet access requirements, and a search for more effective and affordable space - based alternatives. The opportunity for worldwide, fast internet access via networks of LEO satellites is one of the [3] most visible developments in satellite communication systems. Low - Earth orbit (LEO) satellites are designed to [4] communicate with one another, forming a linked network.

Mega Satellite Networks:

The formation of large constellations [7], [8] of satellites is one of the most important advances in satellite communications. They consist of several small satellites that operate in low Earth orbit (LEO). Corporations like SpaceX's Starlink, OneWeb, and [9] Amazon's Project Kuiper are at the beginning of this evolution that claims to offer worldwide web access, resulting in an age of low - latency, fast communication. To deal with rapid data transfer rates, [10], [11] Mega constellations regularly study high - frequency bands like the Ka - band and V - band. These bands feature the possibility for enhanced data capacity; [12] however, they also pose reception issues due to the Earth's atmosphere. Administrators use modern technologies such as adaptive modulation and coding [5], inter - satellite communications, and software - defined satellites to efficiently handle such huge constellations. Some of the innovative techniques used in mega constellations include:

***AMC - Adaptive Modulation and Coding*:** It is used to customize modulation and error correction coding methods by real - time network parameters. Satellites can face various levels of noise and poor connectivity, particularly when connecting with ground - based user interfaces. [5], [13] It guarantees that the most appropriate modulation and coding techniques are used to improve spectral efficiency while preserving network consistency.

***Inter Satellite Links*:** It enables satellites within a constellation to interact directly with each other, [14, 15] reducing dependency on ground stations and increasing reliability and overall connectivity. ISLs provide quick transfer of data and efficient flow of traffic throughout the constellation.

***Software Defined satellites*:** It is essential in the flexible reconfiguration of networks so that the satellite constellation will adjust to fluctuating [16] connectivity patterns while managing the network's load smoothly.

***Phased Array antennas*:** They provide the ability to digitally control the antenna beams of satellites, which is vital in mega constellations since it enables accurate beam shaping, [17, 18], allowing spot beams to aim at areas or consumer endpoints. This reduces [11] transport delays, enabling data to travel more efficiently through [18] shorter ways via the satellite network thus assuring low - latency connections, which is crucial for real - time systems.

***Laser Crosslinks*:** These provide high - speed, packed with data interaction among constellation satellites, leading to increased [19] inter - satellite connection and information transfer features. The network develops less susceptible to unknown issues, like noise or satellite breakdown [20], by building several ways to communicate among satellites. If the link between devices fails, data can be diverted through different channels, retaining network stability.

LEO Satellite Communication Frequency Bands:

To manage high data transfers and [21] enhance connectivity features, satellites in low - earth orbit (LEO) utilize a multitude of frequencies. The Ka - band and V - band are the two crucial bandwidths used by LEO satellites, each with its own set of benefits and drawbacks.

a) Ka - Band (26.5GHz to 40GHz): It is renowned for its high frequency, allowing for a major rise in data storage. The Ka - band is used for quick transmission of data by LEO satellites, [11] thus making it ideal for fast internet access, live video broadcasting, and many other applications that require lots of data. This frequency range is very useful for mega constellations that aim to provide global connectivity with an emphasis on fast digital services [6, 22]. Nevertheless, a major issue with the Ka - band remains that it's prone to signal degradation [23] in the Earth's atmosphere, notably during severe weather.

b) V Band (40GHz to 75GHz): It is ideal for short - distance, high - data - rate networks. This bandwidth is useful for applications such as [14] inter - satellite links (ISLs), that provide direct interaction [24] between satellites in a constellation. These can offer quick information transfer along with efficient distribution of data. The V - band, like the Ka - band, experiences attenuation of signals within the Earth's environment, which can affect network performance. To overcome this challenge, enhanced antenna technology, like dynamic beamforming, is used to improve the reception of signals while minimizing losses.

Modulation Techniques:

Signal quality in satellite communications can differ considerably owing to aspects like atmosphere limitations, noise, [25] and altitude between the satellite and the user interface.

- ***a)*** ***QPSK*:** When compared to more sophisticated modulation strategies, it provides less spectral efficacy, making it ideal for circumstances in which signal stability is vital, [15] including severe weather or distant communication.
- b) ***16QAM*:** When compared to QPSK, it provides more spectral efficiency, therefore 16 - QAM is commonly used in mega satellite networks for [26] increasing capacity for data as it allows more information to be transferred within the same bandwidth, making it ideal for high - capacity, data - intensive applications.

The constellation can utilize more advanced modulation, like 16 - QAM, to increase the flow of data when there is clear weather and good reception. And it can change to a more durable modulation technique, like QPSK, to maintain an uninterrupted connection during extreme conditions.

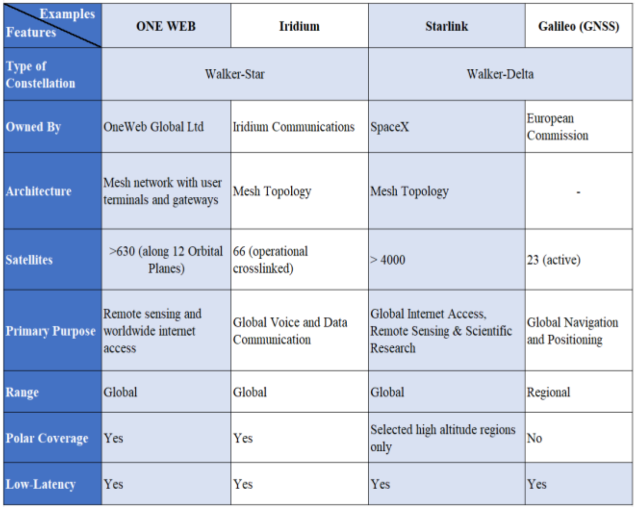
Walker Constellation:

The satellites in Walker Constellation are distributed uniformly across multiple orbital planes (in terms of true anomaly, the planes themselves tend to be identically divided). Its main aim is to ensure that at [27] least one satellite is always accessible from anywhere on Earth, and their careful positioning is designed to fulfill it. Services and programs that require constant connection, [3] like immediate [28] data transfer, World Wide Web access, and vital communication facilities, primarily depend on this feature. In the case of a satellite malfunction or temporary signal loss inside one orbital plane, other satellites in adjoining planes can pick up coverage automatically.

Walker - Star: It is distinguished by the central satellite in each orbital plane, [29] which is surrounded by other satellites evenly placed around it. The center satellite is usually positioned at one of the orbital plane's apogees. The ease of creation and operation of Walker Star constellations is one of their benefits. In large - scale satellite networks, when performance [9] and flexible access are essential, a central satellite acting as the point of focus optimizes the system's design. Walker Star constellations enable consumers anywhere on Earth [28] can link to a satellite inside the network, either for worldwide internet access, mapping, or information transfer operations. Due to the satellite's stable position above the equator in usual geostationary satellite arrangements, the poles often face reception thresholds. Walker - Star constellations can surpass the issue by using satellites in polar orbits to offer broad and continuous service even in high - latitude and northern areas.

Walker - Delta: Walker Delta constellations are a flexible and comprehensive satellite constellation arrangement that provides [30] many significant services. These are especially ideal for operations that require robust networks, emergency response, and vital communication capabilities. A Walker Delta constellation is characterized by the placement of several satellites in each orbital plane in the form of a triangle or delta. The triangular configuration of satellites allows for better transmission of data dispersion. Each satellite in a plane broadcasts information uniformly and [28] efficiently by sharing the workload. This load - balancing feature is critical for maximizing the data flow, minimizing jams, and avoiding network delays when many users access the network at once.

Table 1: Examples of Walker Constellation [2, 31 - 33]



Features \ Examples	ONE WEB	Iridium	Starlink	Galileo (GNSS)
Type of Constellation	Walker-Star		Walker-Delta	
Owned By	OneWeb Global Ltd	Iridium Communications	SpaceX	European Commission
Architecture	Mesh network with user terminals and gateways	Mesh Topology	Mesh Topology	-
Satellites	>630 (along 12 Orbital Planes)	66 (operational crosslinked)	> 4000	23 (active)
Primary Purpose	Remote sensing and worldwide internet access	Global Voice and Data Communication	Global Internet Access, Remote Sensing & Scientific Research	Global Navigation and Positioning
Range	Global	Global	Global	Regional
Polar Coverage	Yes	Yes	Selected high altitude regions only	No
Low-Latency	Yes	Yes	Yes	Yes

3. Simulation Framework

This simulation model closely resembles the characteristics of the commercial constellation OneWeb's Low Earth Orbit (LEO) satellite link analysis method. The goal of this framework is to provide insights into a simplified satellite network's distance and geometry analysis, in addition to link performance analysis.

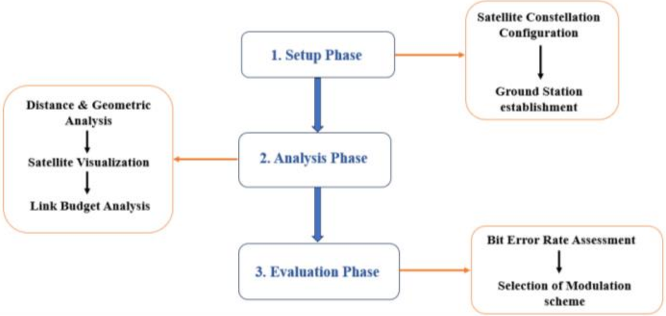


Figure 1: General Structure for Simulation Model

A. Setup Phase

Walker - Star Satellite Constellation

The Walker - Star satellite constellation is created in the first stage of the model. The constellation comprises 12 orbital planes, each with 12 satellites. These satellites orbit the Earth 950 kilometers above the surface. The phasing value 11 indicates that they are separated by 11 orbits. This guarantees that the satellites are dispersed uniformly and cover various portions of the Earth as they circle. It is designed for optimal range and interconnectivity through appropriate phasing parameter adjustment. This design allows continuous global coverage. The satellite positions are depicted in the MATLAB - based satellite scenario ***Figure 1*** based on the parameters provided.

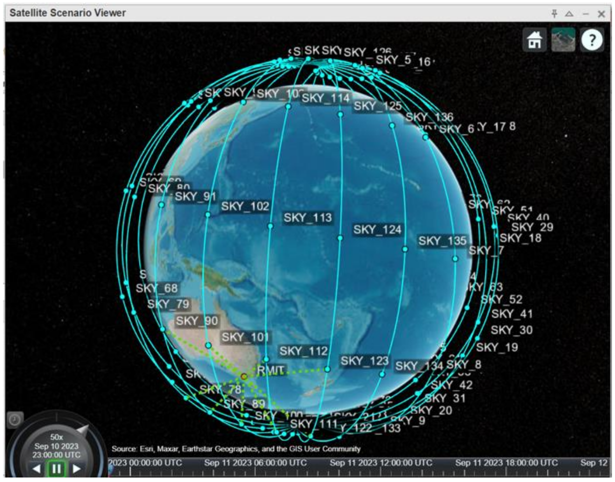


Figure 2: Walker - Star Constellation

Ground Station

At RMIT University, a ground station is positioned as the link establishment point of reference. The MATLAB function "access" is used to establish the virtual link between the ground station and the satellite network. As a result, a connection that allows data transmission between the ground station and satellites is set up.

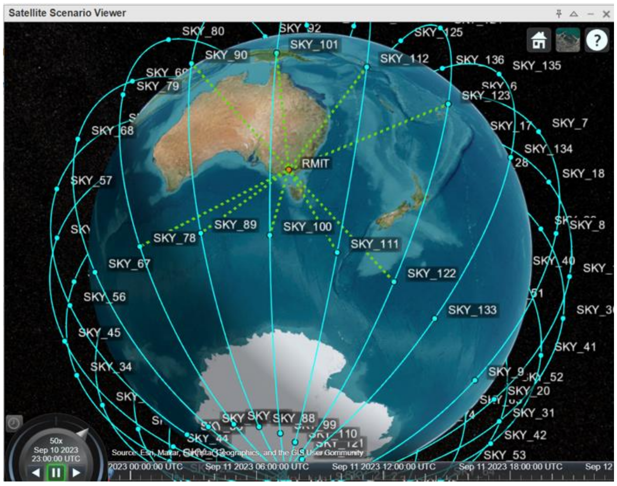


Figure 3: Link with the Ground Station (RMIT Campus)

B. *Analysis Phase*

Geometric Analysis

Elevation angles are used to determine which satellites are above the zenith with the ground terminal. Satellites that have an angle of elevation greater than zero are interpreted to be above the local horizon. It is possible to calculate the ranges between the ground terminal and these satellites. The Skyplot option in MATLAB is used for displaying the azimuth and elevation positions of these satellites which will be discussed in the results section.

Link Performance Analysis

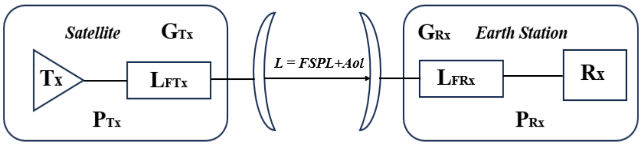


Figure 4: Link Budget Analysis Layout

The satellite nearest to the ground station is determined, and its distance is obtained. A systematic link budget evaluation is done, considering both transmitter and receiver attributes. This evaluation considers the satellite's transmitted power in addition to the feeder losses. The simulation model offered uses 19.100 GHz from the downlink frequency band (19.100 - 19.120 GHz) for a variety of reasons. It assures the satellite communication system functions within the accessible spectrum while complying with global and national standards. In addition, at a frequency of 19.100 GHz, the K - band is utilized for fast data transfer operations such as communications via satellite and cellular networks. Since K - band wavelengths are relatively short, more compact, and smaller antennas can be used. These frequencies are less occupied than other frequency bands, which are susceptible to more interference owing to a wide variety of applications. The reception features of the ground station, such as antenna diameter and efficiency, are given. These computations are required for determining the received power at the ground station. The Boltzmann constant and receiver noise temperature are used to calculate the noise power spectral density at the receiver. The signal - to - noise power spectral density (SNR) and energy per bit - to - noise power spectral density (Eb/No) are calculated using this data.

C. *Evaluation Phase*

Bit Error Rate (BER) Assessment

Bit error rate (BER) calculations for two modulation schemes, 4PSK and 16QAM, are executed to evaluate the link's data transfer potential. The simulation model creates arbitrary data and modulates it using the modulation schemes. To simulate the communication channel, white Gaussian noise is introduced to the signal. To compute the BER, the received data is demodulated and compared to the original data. Furthermore, theoretical BER is calculated to offer a reference for the link's expected performance. A range of Eb/No values is added in the simulation to examine the impact of SNR variations on BER for both 4PSK and 16QAM.

4. Results and Analysis

a) *SKYPLOT*

The satellite locations on the orbital plane are estimated by considering the true anomaly, argument of latitude (which is utilized to calculate the position of each satellite inside an orbital plane), and inclination angle. This calculation's results provide a complete overview of how satellites are placed in orbital planes, giving the basis for thorough link planning and analysis.

The skyplot can be used to investigate possible coverage gaps or instances of satellite inaccessibility. Researchers can detect parts of the sky where no satellites are present by examining the distribution of visible satellites, indicating the demand for more ground stations. Skyplot in ***Figure 5*** depicts the presence of satellites with positive elevation angles, indicating the area of space from which communications can be effectively intercepted. These satellites are shown by red markers on the Skyplot, allowing for a quick inspection of their location relative to the viewer.

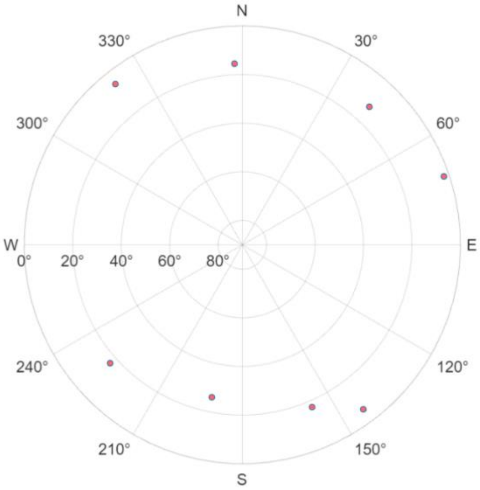
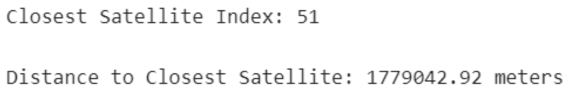


Figure 5: Skyplot

Link Performance Analysis – as shown below the closest satellite in the constellation using the following command:

```
% Index of the closest satellite
 [minDistance, closestSatelliteIndex] = min (distances);

% Get the distance to the closest satellite
closestSatelliteDistance = distances (closestSatelliteIndex);
```



```
Closest Satellite Index: 51

Distance to Closest Satellite: 1779042.92 meters
```

Figure 5: Nearest Satellite Distance Result

The distance obtained will be utilized in the link budget analysis as it affects both the path loss and the received signal power.

b) Link Budget Analysis

FSPL (Free Space Path Loss) – measures the degradation of signal strength as it passes in open air from the satellite to the ground station. Because of the significant range between the ground station and the satellite, the resultant FSPL is 183.0744 dB, which is relatively high.

Power received at the ground station – It depicts the signal power obtained at the ground station after considering variables like transmitter power, antenna gains, and communication path losses (atmospheric and other losses). The ground station's received power is - 119.6347 dBm implying that the received power is substantially less than the transmitted power because of significant distance and degradation.

NPSD (Noise Power Spectral Density) – The intensity of noise from the surroundings in the receiver can be measured by NPSD. The result is - 174.625 dBm/Hz, which indicates the level of thermal noise in the receiver's bandwidth.

SNR (Signal to Noise Power Spectral Density Ratio): The SNR is estimated as 54.9903 dBm/Hz, implying a high signal - to - noise ratio which is beneficial for stable transmission. A higher SNR indicates that the signal is much better than the surrounding disturbance.

Eb/No (Energy per bit to Noise Power Spectral Density) – an important factor in measuring the overall performance of wireless networks. The Eb/No is - 203.4368 dB/Hz, demonstrating that there is ample power per bit to mitigate the impact of noise and ensure uninterrupted transmission. Despite the significant range between the satellite and the ground station, the high SNR and Eb/No figures indicate that the connection fulfills the requirements for reliable data exchange.

Bit Error Rate (BER) Calculations:

4PSK – The bit error rate (BER) for 4PSK modulation is 0.506, indicating that about 50.6% of the acquired bits are incorrect. A BER of 0.5 indicates an arbitrary outcome, showing that the system's efficiency is a bit inferior to random. The theoretical BER for 4PSK, estimated as 0.5, matches up to the empirically obtained result. The theoretical value reflects the best possible performance under optimal circumstances with the absence of noise or disturbance. The significant match between theoretical and practical statistics indicates the system functions correctly for 4PSK modulation.

16QAM – Based on 59, 942 errors, the binary coding BER for 16QAM modulation is 5.00e - 01. According to this, around 50% of the received data is wrong, which is quite high. It could mean the system is having trouble decoding the 16QAM signal. Given 59, 819 errors, the Gray coding BER for 16QAM is found to be 4.98e - 01. Gray coding is used to minimize the effect of errors, and the slightly reduced BER in comparison with binary coding implies a small performance benefit. The theoretical BER for 16QAM is 0.75, which is much more than the practically recorded results. This means that 16QAM could operate better given optimal circumstances. The variation between the theoretical and empirical data shows that noise or interference could be influencing the efficiency of the system.

***Analysis of 2 Modulation Schemes*:**

The Eb/No value used in this evaluation is - 203.4368 dB/Hz, along with a range of values from Eb/No - 5 dB to Eb/No + 5 dB were examined. The Bit Error Rate (BER) statistics for both modulation techniques were determined for this spectrum of Eb/No values, which serves as an important metric of a communication system's efficiency. The BER vs. Eb/No for 4PSK and 16QAM is presented as a function of Eb/No. The result in ***Figure 6*** indicates that 16QAM has higher BER values than 4PSK across the range of Eb/No values reviewed, suggesting that 4PSK is a more resilient modulation strategy under the current circumstances.

5. Suggestion

According to the research results and BER comparison, it is suggested that the terminal utilizes 4PSK modulation. It has a lower BER across the Eb/No range, demonstrating enhanced stability and efficiency in the presence of interference and noise. With the implementation of 4PSK, the terminal can accomplish higher error - resistant interaction, which is essential in preserving the transmission of data quality and integrity, even during harsh circumstances.

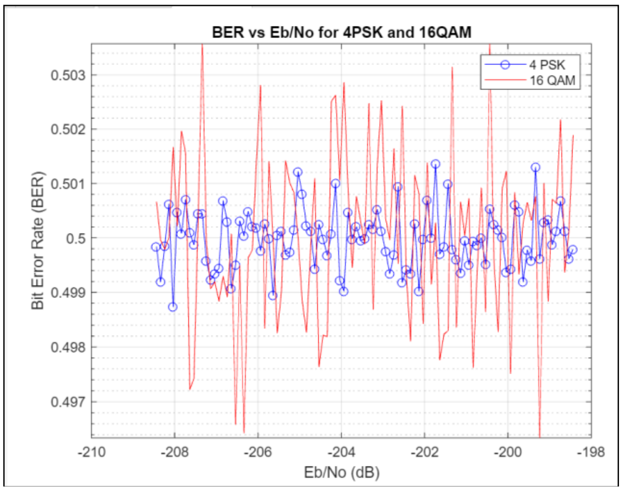


Figure 6: Comparison of BER for 4PSK and 16QAM

Methods to improve the Bit Error Rate (BER):

Enhancing the communication system's Bit Error Rate (BER) is vital for maintaining consistent and effective data delivery.

- ***Adaptive Modulation and Coding*** **–** To maximize the delivery of data, Adaptive Modulation and Coding (AMC), is an essential method used in modern systems of communication. It adjusts the coding rate and modulation method automatically. Signal - to - noise ratio (SNR), fading, disturbance, and other channel factors are considered as it constantly evaluates the overall performance of the connection and quickly adjusts the modulation and coding configurations. AMC chooses higher - order modulation techniques (such as 16 - QAM or 64 - QAM) and lower coding rates whenever the signal - to - noise ratio (SNR) is high, and the channel is noise - free. This improves the speed of data and effective spectrum utilization, optimizing the bandwidth accessible. it changes to more resilient modulation methods (like BPSK or QPSK) and higher coding rates if the channel quality decreases because of factors that include interference, fading due to multiple paths, or disturbances. These techniques are less vulnerable to errors, so they ensure accurate interaction despite challenging circumstances.

- ***Forward Error Correction*** **-** A type of error - control coding that adds redundancy to transmitted data, enabling the receiver to recognize and fix flaws without necessitating relays from the sender. This technique tends to be useful when relays are either unavailable or develop excess delay. FEC functions by encoding data at the transmitter with error - correcting codes and recovering it at the receiver. It can be accomplished by employing codes like as Reed - Solomon Codes (which exhibit significant error - correcting characteristics), Turbo Codes (convolutional codes that function similarly to the Shannon Limit), and Low - Density Parity - Check (LDPC) Codes (which are effective for transmitting large amounts of data).

- ***MIMO (Multiple Input Multiple Output) & Beamforming*** **–** It includes utilizing multiple antennas at the transmitting and receiving ends, which can considerably enhance BER via spatial diversity (the signal passes through numerous spatial routes, allowing it to reduce dispersion and signal loss resulting from interference) and multiplexing (enables various streams of data to be carried at once through the same frequency, enhancing data capacity instead of elevating transmission power). However, Beamforming is an aspect of MIMO that distributes the power of the broadcast signal in certain directions. It decreases noise and improves received signal strength by directing the signal toward the receiver, thereby optimizing BER efficiency.

6. Conclusion

In conclusion, this research project offered useful information about the design and evaluation of a Low Earth Orbit (LEO) satellite constellation like the OneWeb system. The study focuses on two main areas: distance and geometric assessment and link assessment. It revealed vital data regarding the system's spatial distribution and reach, highlighting the relevance of the phasing variables utilized. The Link Budget assessment included an extensive review of variables, which indicated that, regardless of significant free space path loss, the link between the ground station and the nearest satellite retained a considerable signal - to - noise ratio (SNR) along with energy per bit - to - noise power spectral density (Eb/No). In addition, the study explored both modulation schemes, 4PSK & 16QAM, and decided that 4PSK is a more resilient option for the terminal given the circumstances analyzed. Additional optimization of the LEO constellation architecture, along with investigation of sophisticated methods such as adaptive modulation and coding, forward error correction, and MIMO/beamforming, potentially strengthen the performance and productivity of LEO satellite networks in the future.

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