The Hong Kong Polytechnic University
Department of Computing

COMP4913 Capstone Project
Final Report

Simulation and Analysis of Inter-satellite Communication for Real-Time Data Downloading

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1. Introduction

1.1 Motivation

In recent times, 4,700 Low Earth Orbit (LEO) satellites have become increasingly popular, with 4,700 currently orbiting the Earth below 2000 kilometers (Union of Concerned Scientists, 2022). These satellites have diverse uses such as communications, military reconnaissance, spying, and imaging applications, with an average of 115 small LEO satellites being launched annually from 2014 to 2023 (Sebestyen et al., 2018). One major advantage of LEO satellites designed for communication is the reduced signal propagation delay in LEO. The environment in LEO provides lower propagation delay and is able to communicate with Ground stations with utmost efficiency (Shustova, 2022), resulting in low latency, high bandwidth, and universal internet connectivity (Vasisht et al., 2021). Meanwhile, LEO satellites are closer to the Earth's surface, so imaging satellites will also be able to capture better and more detailed pictures (Shustova, 2022).

However, the communication range of LEO satellites exist a coverage issue, and limited number of ground stations. It results in an LEO satellite may fly for many hours to end up in the communication scope of a ground station and taking a long time for an LEO satellite to download the data to the ground.

1.2 Background and Problem Statement

Low Earth Orbit (LEO) satellites face communication challenges due to their limited coverage range, which is smaller than that of higher-altitude satellites. Communication with ground stations is only possible when the satellite is in its visibility scope. The duration of the visibility and the communication varies for each LEO satellite passing over the station since LEO satellites move too fast over the Earth. (Cakaj et al., 2014). As a result, an LEO satellite may take several hours to enter the communication scope of a ground station. This problem is compounded by the limited number of ground stations, leading to longer wait times for an LEO satellite to download data to the ground. The data satellite must wait at the satellite before it comes in contact with a ground station (Vasisht et al., 2021).

These limitations make it challenging to achieve the strong real-time constraints for data downloading in LEO communication systems. Which requires to guarantee events can be completed in a set amount of time. The unpredictable nature of LEO satellite movement and distribution makes it difficult to complete data transmission in a set amount of time when the path of data transmission is not guaranteed.

Inter-satellite communication offers a promising solution to overcome the challenges of real-time data downloading, even with limited ground stations. In this approach, an LEO satellite can transfer its data to another satellite that can communicate with a ground station, increasing the likelihood of meeting the download deadline. This project aims to study the feasibility of inter-satellite communication in meeting real-time data downloading requirements.

This project will simulate communication behavior between LEO satellites and ground stations, as well as between multiple satellites, to analyze their communication capabilities and delays. To determine the best path for downloading data, the simulation will investigate all possible options available to an LEO satellite and identify paths that can meet the download deadline. Overall, this study will provide valuable insights into the potential of inter-satellite communication to improve the efficiency of LEO communication systems.

1.3 Aim and Objectives

The primary objective of this project is to analyze whether the deadline for data downloading can be met when the data on an LEO satellite is transferred either directly to a ground station or via another LEO satellite, considering a configuration of an LEO satellite constellation and a set of ground stations. To achieve this objective, several sub-tasks need to be accomplished.:

1. Simulation: to simulate the communication behavior
    a. Simulating the position of each satellite in space at a given time allows for the evaluation of communication feasibility between two satellites.
    b. Simulating the observation scope of a given point involves evaluating related parameters to determine whether a satellite is within range.
    c. Simulating the communication scope of a ground station involves evaluating related parameters to determine whether a satellite is within range for communication.
    d. Simulating data transfer latency involves evaluating the time it takes for data to be transmitted, whether between satellites or between a satellite and a ground station.

2. Optimization

   There can be multiple paths for a satellite to download the data to the ground. Based on the simulation capability, an optimization algorithm will be developed to find the shortest communication path and check if the communication along this path can meet the data download deadline.

To simulate the communication between Low Earth Orbit (LEO) satellites and ground stations, the simulator will use real LEO environment features and space geometry. It aims to compute the real-time capabilities of a group of LEO satellites in data downloading by simulating the environment of LEO and referring the existing satellites to obtain data close to reality. Meanwhile, the simulator simulates the LEO environment with space geometry and satellite communication.

The simulator will incorporate existing satellite data to ensure the accuracy of the simulation. It will model LEO satellite visibility and simulate data transmission paths, considering multiple factors such as orbit, observation point, and ground station.

Overall, the project's outcome will be a simulator that displays the orbits of LEO satellites, data transmission paths, and transmission delays. Users will be able to customize the simulation by selecting observation points, ground stations, orbits, and satellites. The simulator will enable users to find the path of data transmission and assess the transmission delay.

2. Project Design and Methodology

The Project Simulation consists of the visibility Model, Communication Delay Model, and Path Decision Model. Their relationship is shown in Fig. 1.

The simulator begins by using the Visibility Model for observation to use the positions of the observation point and the LEO satellite set to identify the satellite within the observation scope, which serves as the starting node in the data transmission path. Next, the Path Decision Modeling component uses the Visibility Model for inter-satellite communication to identify all the satellites within the communication scope of the current satellite. The path decision algorithm is then used to select the next node. The Communication Delay Model is then utilized to calculate the delay to the next node, while the Visibility Model for Satellite to Ground Station Communication is used to determine if the next node is within the target Ground Station communication scope. If so, the algorithm model ends and the communication delay model calculates the delay to the Ground station. If not, the Path decision modeling iteration continues.

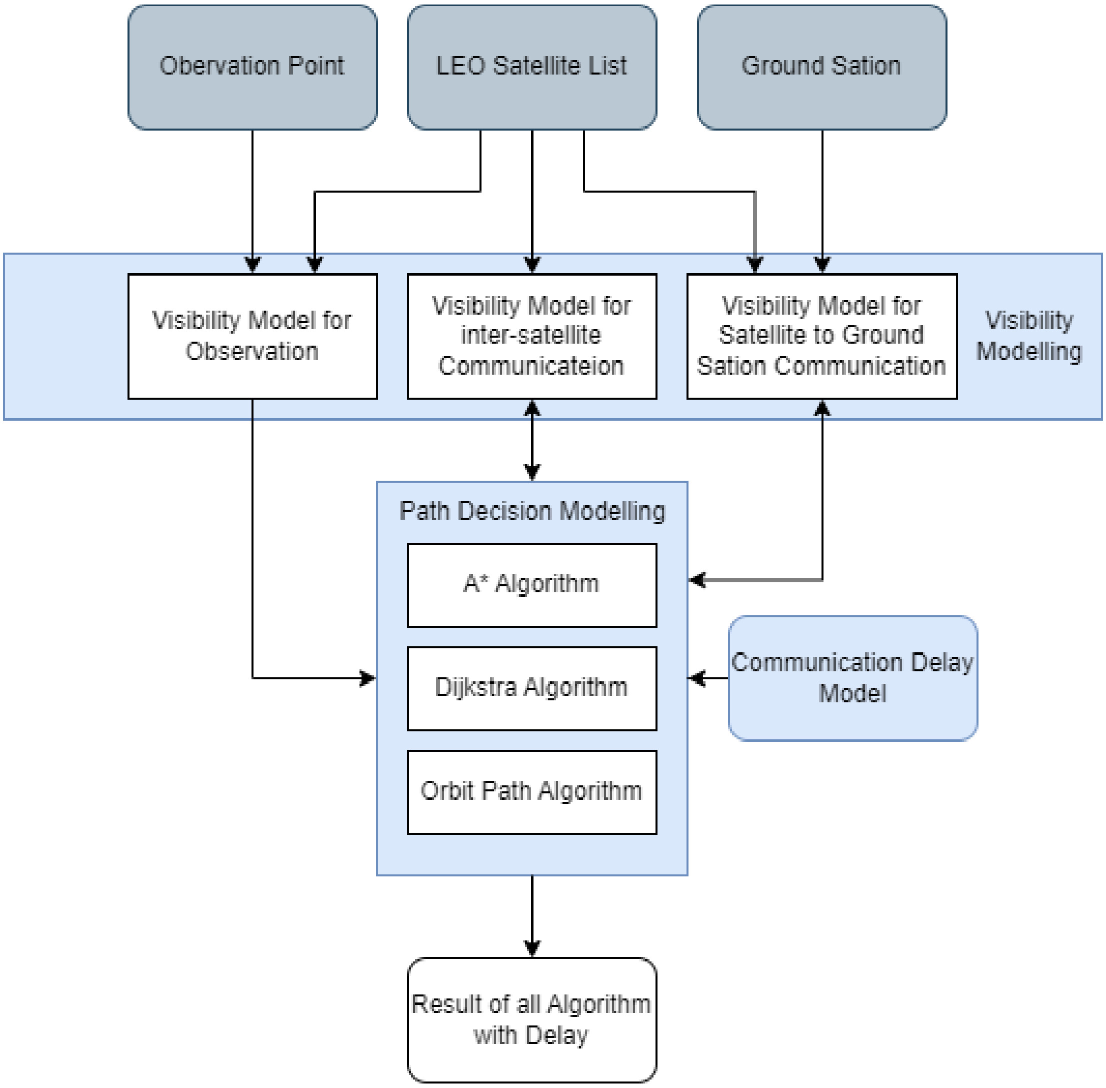


Fig. 1 Flowchart of all Component

2.1 LEO Satellite Space Geometry Modeling

In space geometry modeling, there are mostly using mathematical algorithms in space geometry. These algorithms will be developed with Python and use the "NumPy" library for assistance.

To local the ground target and Satellite in space, the Earth-Centered Inertial (ECI) is used as the coordinate system. ECI coordinate system is a 3-dimensional Cartesian coordinate system with the original fixed center in the Earth's mass center, which remains fixed with respect to the stars.

Except for using the (x, y, z) to represent the point in the coordinate system, right ascension (denoted by α) and declination (denoted by δ) are used to represent the angular position of the point. The right ascension of point P in Fig. 2 is the angular distance of point P which is measured eastward along the celestial equator from the x-axis of an ECI coordinate to point P. The declination is the angular distance from the equatorial plane to point P in Fig. 2 which is measured along the hour circle passing through point P.

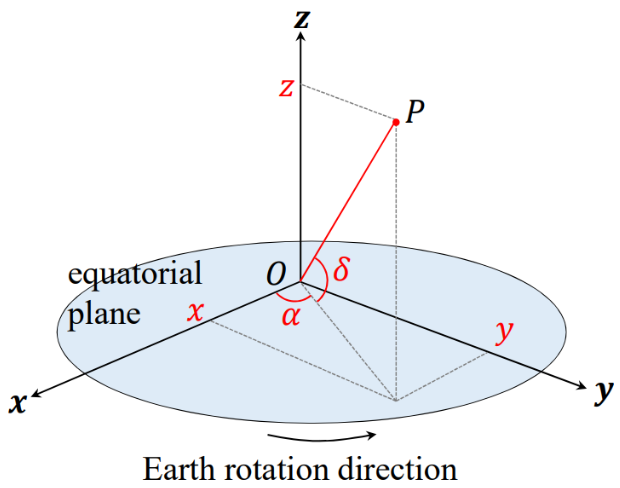


Fig. 2 Elements of ECI coordinate system

Fig. 2 shows the ECI coordinate and the position parameters of point P. r in Fig. 2 is the distance from point P to the original point in the ECI coordinate system. The (x, y, z) value in the coordinate system can be computed by the equations below.

$$x = r * \cos \delta * \cos \alpha$$

$$y = r * \cos \delta * \sin \alpha$$

$$z = r * \cos \delta$$

Earth is an ellipsoid very close to a perfect sphere. But for simplicity of the calculation, the Earth is assumed as a perfect sphere. The self-rotation of the Earth is eastward along the celestial equator with an angular speed of 2π per day. Because of the self-rotation of the Earth, the (x, y, z) value in the coordinate system and the right ascension of the point following the self-rotation and satellite movement continue to change in the ECI coordinate. But the latitude of the point, coinciding with its declination, remains unchanged.

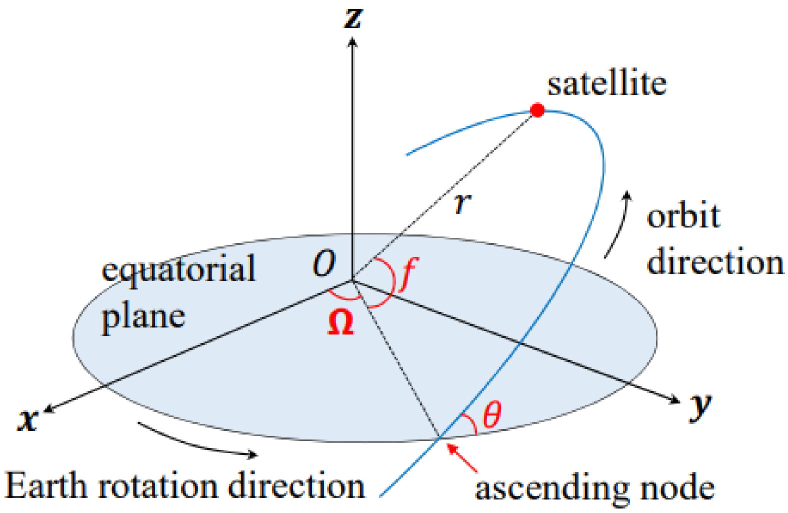


Fig. 3 Elements of Satellite Orbit

In Fig. 3, point P has a longitude (λ) and a latitude (φ). At time t_0, P has a right ascension of α_0 and a declination of δ_0. After an amount of time passed, a new right ascension α_t, new declination δ_t can be computed by the following equations. Where ω_e denotes the angular speed of self-rotation of the Earth ($\omega_e = 2\pi$/day).

$$\alpha t = (\alpha_0 + t \cdot \omega_e) \bmod 2\pi;\ \delta t = \delta 0$$

Because the altitude of the LEO satellite is low which take the orbit is close to the perfect circle. Therefore, in this project, the satellite orbit is assumed as a circular orbit. There is orbit information shown in Fig. 3 used to describe a satellite as below.

- R: the radius of the orbit

- θ: the inclination angle from the equatorial plane to the orbit plane which is measured above the equatorial plane when θ in $\left[0,\frac{\pi}{2}\right]$, the orbit is in the same direction as the Earth rotation. when θ in $\left[\frac{\pi}{2},\pi\right]$, the orbit is in the opposite direction as the Earth's rotation.

- **Ω**: the right ascension of the ascending node which is the point where the orbit crosses the equatorial plane northward.

- F: the true anomaly which is the angular difference from the equatorial plane to the initial position of the satellite.

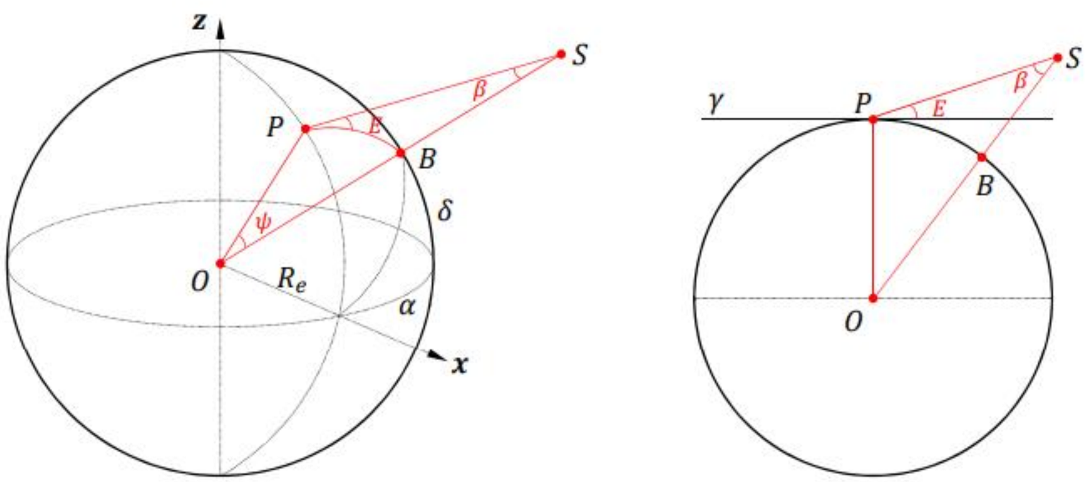
2.2 LEO Satellite Visibility Modeling

2.2.1 Visibility Modeling for Observation

To model the characteristics of the visibility scope of the satellite for the observation target, the visibility scope is determined by the altitude of the satellite and the capability of the satellite camera. As Fig. 4, S is the satellite, P is the observation target, and O is the center of Earth. There is a sub-satellite point B which is a point on Earth's surface intersecting with the line O to S. γ is the plane that is tangent to the Earth at P.

The camera of the satellite is mounted on a head and initially points to the sub-satellite point. At the run time, the camera can swing for an off-nadir angle (β in Fig. 4) to take an image. The off-nadir angle is limited, so the visibility scope of an LEO satellite is limited by the maximum off-nadir angle. If the satellite is right above the observation point P, the off-nadir angle will be 0.

The current β can be computed with the observation target and the satellite. If the current is smaller than the maximum β and the satellite is above the γ plane, then the satellite can capture the image of the observation target.



(a) Stereoscopic view (b) Slice view

Fig. 4 Observation Visibility

Because the position of the observation target and satellite is continuously changed by the Earth's rotation and satellite movement. For future development of communication, the visibility model can compute the time window of the satellite's ability to visit the observation target by comparing the β at any time with the maximum β.

2.2.2 Visibility Modeling for Satellite to Ground Station Communication

To communicate with the ground station, the satellite must be within the communication scope of the ground station. The visibility model is used to find out if the ground station is visitable by a satellite. The main determining factor of the modeling is the elevation of the ground station (as shown by angle E in Fig. 4) which is the angle to measure the perpendicular to the earth's surface. if the elevation angle of the ground station is 90 degrees, it means the satellite is right above the ground station. The elevation angle can be changed by the Earth's rotation and satellite movement. When the elevation angle is too small, the satellite will not able to communicate with the ground station.

Because the visibility model of communication is similar to the visibility model of observation, the visibility model of observation can be reused to compute the communication scope. P in Fig. 4 can seem like the ground station. According to the principles of triangles, there is a fixed relationship between the angle β and elevation E, so

$$R_{Earth} * \cos E = r * \sin \beta$$

The minimal elevation is typically specified by the ground station. In the range [0◦, 90◦] when E increases, β decreases. So, the maximal β can be computed by the above equation. When the current β is smaller than the maximal β, the satellite is within the communication scope. And able to compute the time window of the satellite's ability to visit the ground station by comparing the β at any time with the maximum β.

2.2.3 Visibility Modeling for inter-Satellite Communication

If the satellite is not within the communication scope of the ground station, the data can be transferred to another satellite. For this purpose, a visibility model is needed to find out the satellite communication scope. The visibility model in inter-satellite visibility is different from the satellite to ground station visibility modeling.

Because the distance of inter-satellite communication range is typically unlimited in LEO, so the main determining factor of the model is the communication of two satellites whether being blocked by the Earth. Because the distance of inter-satellite communication range is typically unlimited in LEO, so the main determining factor of the model is the communication of two satellites whether being blocked by the Earth. The maximum off-nadir angle (β in Fig.5) can be computed by the following equation when S2 is the satellite containing the data.

$$\beta_{max} = \sin^{-1}(R_{Earth}/r_2)$$

The current β can be computed by the bisector (shown as h in Fig. 5) of r_1 and r_2. When β is bigger than β_{max}, both satellites can communicate with each other.

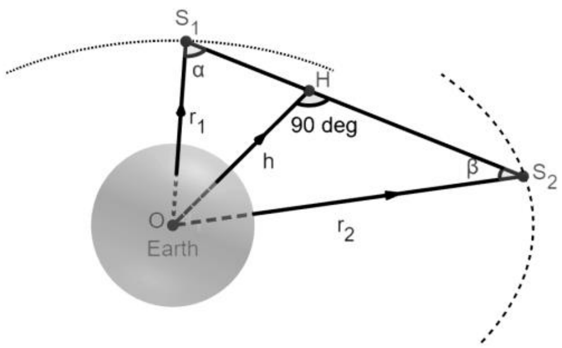


Fig. 5 Inter-Satellite Visibility

2.3 Communication Delay Model

The Delay of inter-Satellite and Satellite to ground station communication is constructed by transmission delay, propagation delay, buffer delay, and process delay.

2.3.1 Transmission Delay(t_t)

The transmission delay is the time taken to transmit a single data packet at the data rate of the Satellite. Formula as below.

$$Transmission\ Delay(t_t) = \frac{packet\_size}{data\_rate}$$

2.3.2 Propagation Delay(t_d)

The propagation delay is the time taken for the signal to travel from satellite to satellite or ground station. Most Satellites usually use radio, its signal speed is 299,775 km/s. Formula as below.

$$\text{Propagation } Delay(t_d) = \frac{distance\_between\_two\ \_object}{signal\_speed}$$

2.3.3 Buffer Delay(t_b)

The buffer delay is caused by cell queuing at each point in the network, which may result from traffic's bursty nature, congestion at the queuing locations (such as ground stations and satellites), or media access control delays.

2.3.4 Process Delay(t_p)

Depending on the level of onboard switching and processing, the data packets may experience extra delays (t_p) at each satellite hop. In high data rate networks that use packet/cell switching, the switching and processing delays are insignificant when compared to the propagation delays.

2.3.5 Total Delay

The total delay for a single communication combines the transmission delay, propagation delay, buffer delay, and process delay. Formula as below.

$$\text{Total } Delay = t_t + t_d + t_b + t_p$$

2.4 Path Decision Algorithm

In this section, algorithms are used to compute the distance between satellites and make the decision to select the next satellite needed to transmit the data. There are three path algorithms is used. They are A*, Dijkstra, and a self-designed Orbit Base Path Algorithm. Algorithms are implemented with the "NumPy" and math library to assist the calculation.

2.4.1 A* Algorithm

The A* Algorithm is a heuristic-based pathfinding and graph traversal algorithm that prioritizes the exploration of nodes based on a combination of the actual distance traveled from the start node and an estimated distance to the goal. The algorithm maintains a priority queue of nodes to explore, selecting the node with the lowest estimated total cost at each step and expanding its neighboring nodes until the goal is reached. In this project, the position of the satellite is time-dependent, and once a satellite is selected as the next node in the path, the communication delay is calculated and updated at the current time. The path cost is defined as the actual distance traveled from the start node, and the estimated distance is the straight-line distance between the current satellite node and the ground station.

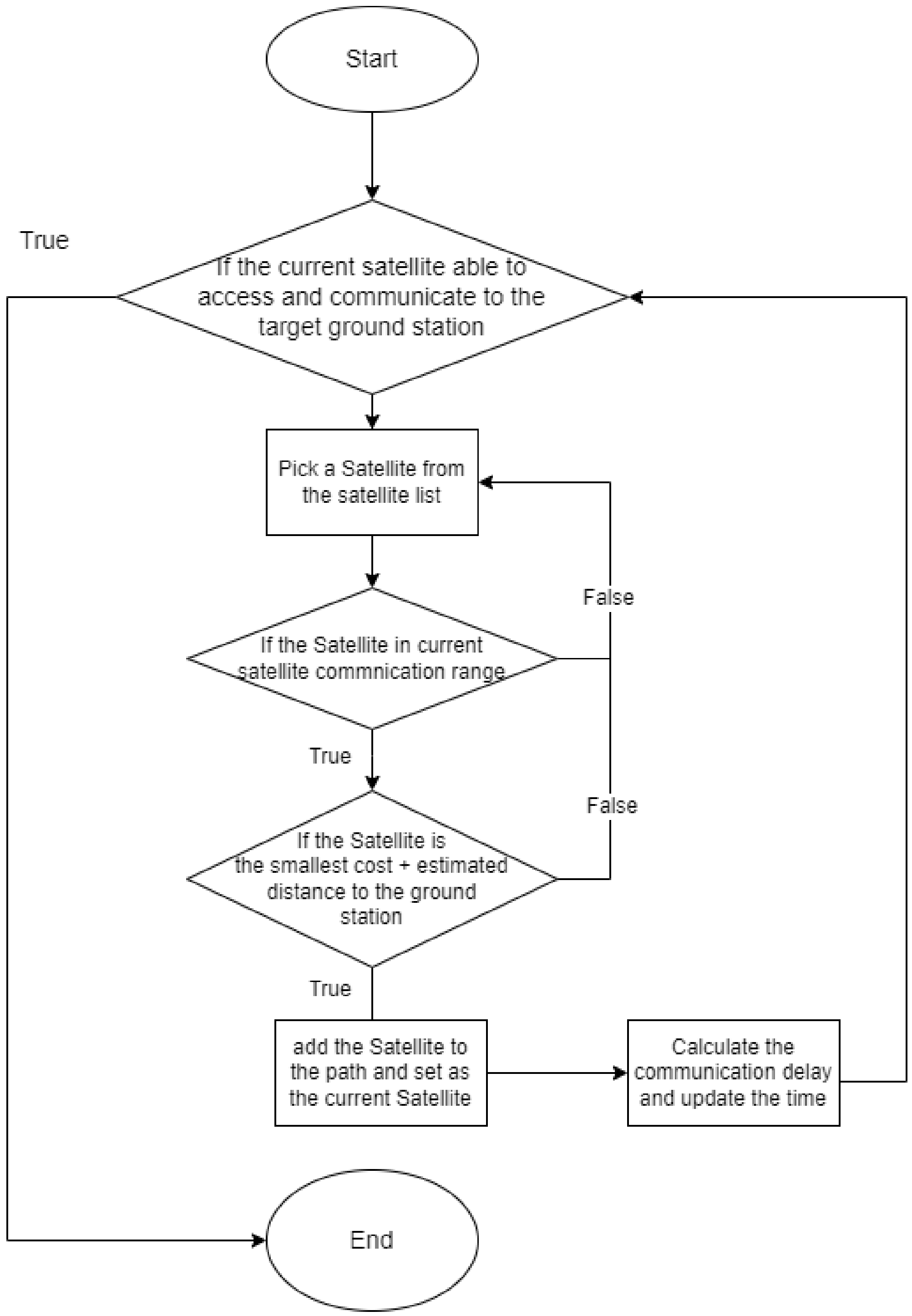


Fig. 6 A* Algorithm Flowchart

2.4.2 Dijkstra Algorithm

The Dijkstra Algorithm begins by selecting a source node and evaluating all of its adjacent nodes, determining the distance between the source node and each of them. The algorithm then chooses the node with the shortest distance from the source node as the next node to visit and repeats the process until it reaches the destination node. As each node is visited, its adjacent nodes are added to the priority queue if they have not been visited before, and their distances from the source node are updated if a shorter path is discovered.

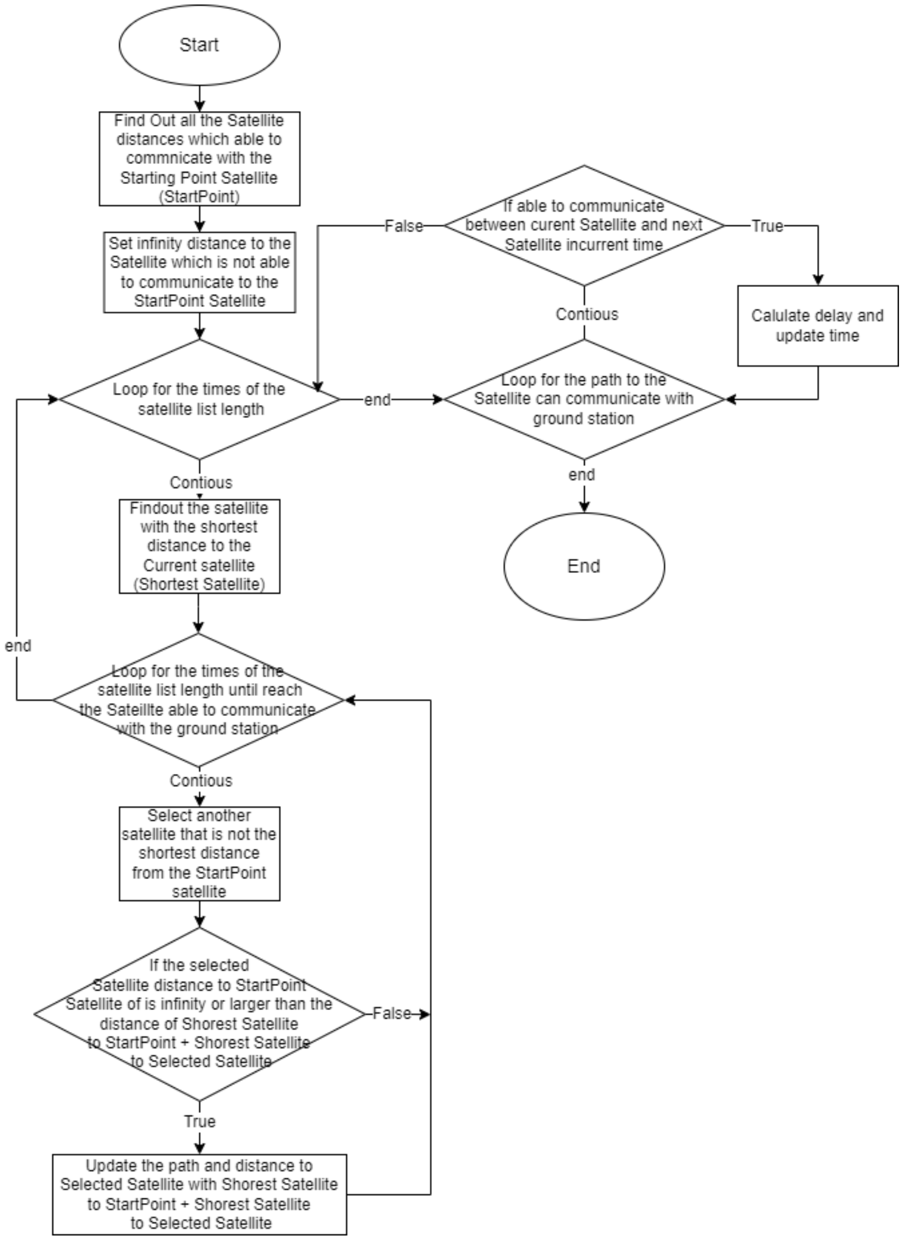


Fig. 7 Dijkstra Algorithm Flowchart

2.4.3 Orbit Base Path Algorithm

The Orbit Base Path Algorithm is a novel algorithm developed specifically for this project. It is based on the concept of transmitting data from one orbit to another, bringing the data progressively closer to the ground station until it can be transmitted directly to the ground station. Before selecting the next satellite to transfer data, the algorithm will find out which orbit beside is closer to the ground station, then select the satellite in the orbit which is the nearest to the ground station to transfer data. Iteration until the satellite is within the communication scope of the ground station.

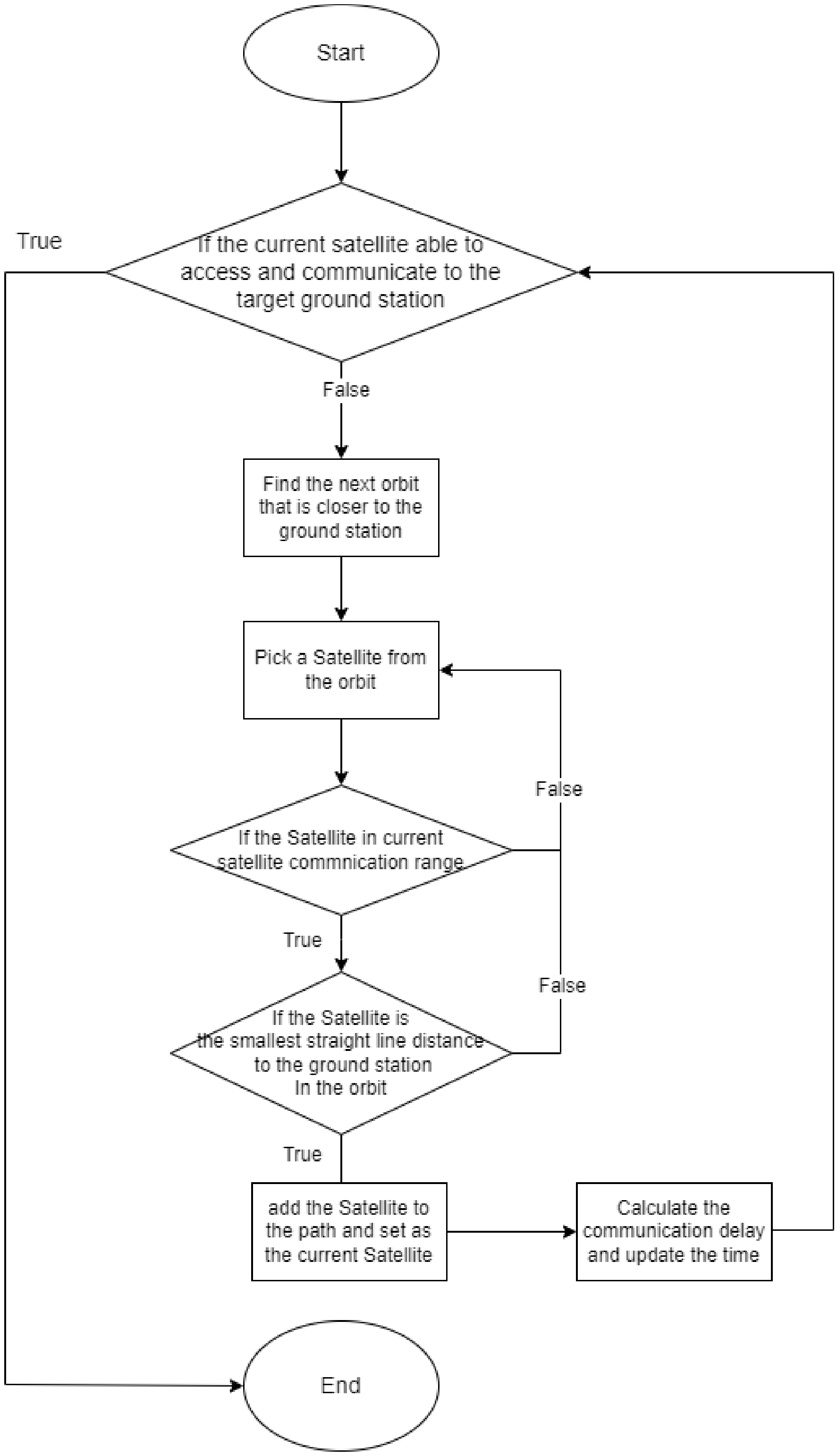


Fig. 8 Orbit Base Path Algorithm Flowchart

2.5 Experiments and Demonstration

To demonstrate the work of this project, the simulator will output the dynamics of the satellites and the potential communication paths for data downloading, and it will also show the shortest path that is found by the decision-making algorithm.

To set up the parameter, a simple graphical interface is developed to set up the parameter of satellite generation and data transmission by using the “tkinter” Library. As below.

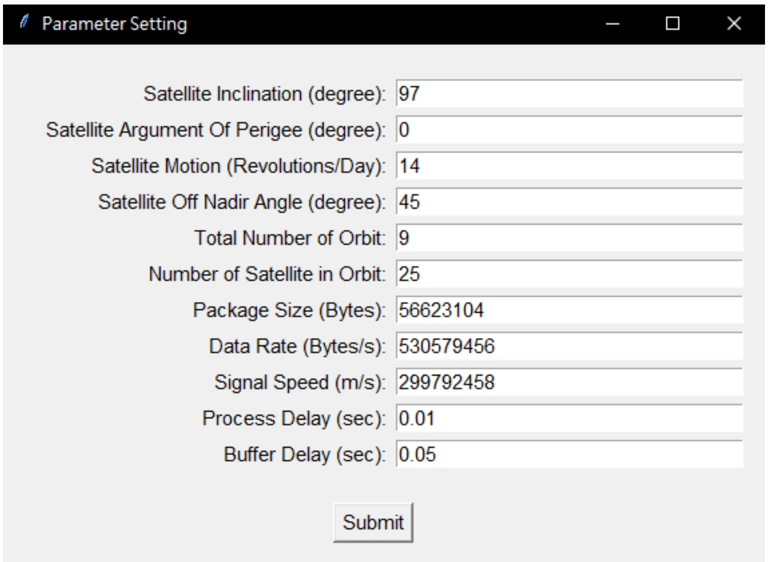


Fig. 9 Setting user interface

To demonstrate the result, a graphical interface is developed to show all the results of each path decision algorithm of the satellite communication and the delay of traditional satellite communication by using the “pyopengl” and “pygame” Library to plot the 3D image of the result as below.

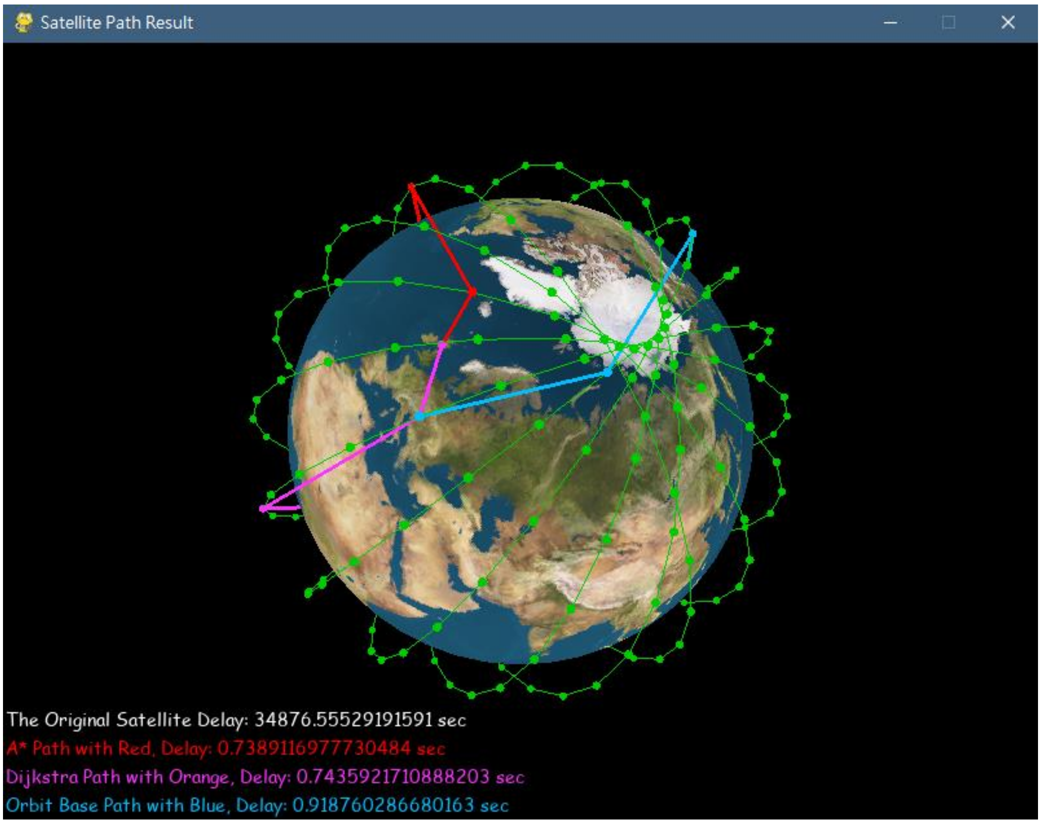


Fig. 10 Result graph user interface

The details of the results will be stored in an Excel file named analysis analysis_result.xls inside the results folder in the project directory.

3. Implementation

3.1 Resources Estimation

3.1.1 Hardware Requirement Estimation

To run this Project, you only need hardware that can run Python files and handle 3D images to display the graphical output of path decisions. This can be achieved with a computer that meets these requirements.

3.1.2 Software Requirement Estimation

To run the simulator for this Project, you only need a software environment with Python versions 3.8 or newer and pip installed for library installations. You will also need a code or file editor, such as VScode, to modify the Ground Station and Observation point positions.

3.1.3 Use of Library

This Project utilizes various Python libraries for different purposes. NumPy and Math libraries are used for performing calculations. xlwt library is used to output detailed data of the path decision result. Tkinter is used for drawing the graphical interface of the settings panel. Lastly, PyGame and PyOpenGL are used for generating the output of the path algorithm in a 3D image.

3.2 Use of Project

3.2.1 Set up Parameter

To set up the parameter of time, position of the ground station, and observation point. The file in Setting Folder from the project directory can be modified.

Table 1 Setting File

Setting file name	Description	Format
main_GROUND_STATION.txt	contain only one ground station as the point data transfer to	Latitude(degree) Longitude(degree)
main_OBSERVATION.txt	contain only one observation point as the point to observe	Latitude(degree) Longitude(degree)
TIME_INTERVAL.txt	define the Starting DateTime of the simulator	yyyy MM dd hh mm ss

3.2.2 Prepare the Environment

To install all the Library used in the project with the same version, a command should be run in the project directory with the following:

```
pip install -r "requirements.txt"
```

3.2.3 Run Simulator

To run the simulator, the main.py in the root of the project directory should be executed with the following command.

```
python main.py
```

Then the simulator will be started.

4. Experimental Evaluation

4.1 Evaluation targets

This project aims to simulate LEO satellite communication using a designed simulator. The simulator considers the parameters of the LEO satellites, ground stations, observation points, and data transmission to determine the optimal starting point for data transfer. Using the path decision algorithm described in the design section, the simulator calculates the most efficient path for data transfer to the ground station. The experiments focus on determining the delay of transmit time required, and the performance of each path decision algorithm. Additionally, the experiments compare the path decision algorithm to the traditional method of satellite data transfer.

In the experiment, it intends to answer the following questions:

- The time used in the traditional method of Satellite transfer data
- Comparing different path decision algorithms
- The average time range for each path algorithm to transmit data

4.2 Results and Evaluation

4.2.1 <u>Traditional Method of Satellite Transfer Data</u>

To test the time used in the traditional method of satellite data transfer, the experiment used a satellite that can observe the observation point as the satellite to carry the data. The simulator time was then increased until the satellite was within the communication scope of the ground station, and the communication delay was added to the delay time.

The parameter for the data transfer remained constant, and only the latitude and longitude were varied to determine the time range. The specific parameter values used in the experiment are as follows:

Table 2 Parameter Setting

Parameter	Value
inclination	97 degree
Argument Of Perigee	0 degree
mean motion	14 revolutions per day
Number of orbits	9
Number of satellites for each orbit	25
Buffer Delay for Each Satellite	50 ms
Process Delay	10 ms
Package Size	54 Mb
Data Rate	506 Mb/s
Signal Speed	299792458 m/s (radio speed)

Using the parameters specified in Table 2 with only one ground station at the same time, the experiment was conducted within a latitude and longitude range of 0 to 360 degrees, and the following results were obtained:

Table 3 Result of the traditional method with a single ground station

Observation Point		Ground Station		Transmit Delay (second)
Latitude	Longitude	Latitude	Longitude	
0	0	0	180	3002.357
270	0	90	180	3082.417
56	261	304	99	3070.627
0	0	0	30	36242.237
0	0	0	60	29586.947
0	0	330 (360-30)	0	233.0875
0	0	300 (360-60)	0	790.717

Based on the results, the average delay for transmitting data from an Earth position to a position opposite on Earth is about 3050 seconds. Furthermore, the comparison of transmit delay with latitude or longitude changes indicates that longitude changes have the most significant impact on the delay.

Table 4 Latitude and Longitude of Ground Station

Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
49.7	8.33	352.853	107.848	36.273	261.769
54.647	40.819	22.117	107.848	33.434	277.451
47.017	33.267	29.692	119.789	45.329	291.675
42.012	26.77	4.245	116.101	52.895	276.046
51.918	28.35	36.454	119.262	54.148	283.773
54.341	32.389	43.952	129.272	43.701	287.988
59.949	7.979	36.029	138.404	47.031	291.5
21.187	348.206	340.408	145.078	5.037	295.888
6.046	45.455	330.981	151.751	353.468	283.068
346.345	36.498	327.362	117.682	343.497	289.374
328.748	24.557	58.127	228.93	350.855	319.579
27.048	47.49	43.025	239.115	329.836	306.935
28.447	55.744	40.136	237.886	310.619	290.779
21.792	80.627	25.289	255.447	333.545	297.101
16.989	98.891	29.191	263.35	18.412	290.603
19.16	81.857	30.712	275.819	18.245	326.78
358.104	102.052	17.614	260.365		

To test the traditional method performance with multiple, the parameters specified in Table 4 are used and the ground station list specified in Table 4 will be used. The experiment was conducted within a latitude and longitude range of 0 to 360 degrees, and the following results were obtained:

Table 5 Result of the traditional method to transmit data

Observation Point		Transmit Delay (second)
Latitude	Longitude	
0	0	3672.955
270	0	3206.124
90	0	256.124
56	261	26.912
0	90	13.053
0	180	1706.125
0	270	32.853

Based on the results, the delay for transmitting data is above 10 seconds. When there not exists a ground station nearby the Satellite orbit, it will cost a large number of delays to transmit the data. Furthermore, the unstable delay of the traditional method is not meet the real-time system constraints.

4.2.2 Average Time Range for each path algorithm

In each path decision algorithm experiment, a satellite is chosen as the starting point, which can observe the observation point, and a satellite within the ground station communication scope is selected as the endpoint. The experiment parameters in Table 2 will be used in the experiment.

Table 6 Result of the traditional method to transmit data

Observation Point		Ground Station		Transmit Delay (second)		
Lat	Long	Lat	Long	A*	Dijkstra	Orbit Base Path
0	0	0	180	0.739	0.740	0.912
270	0	90	0	0.741	0.739	0.740
56	261	304	99	0.747	0.745	0.918
0	0	0	30	0.348	0.348	0.348
0	0	0	60	0.358	0.358	0.526
0	0	0	120	0.728	0.719	1.062
0	0	330	0	0.349	0.344	0.349
0	0	300	0	0.357	0.356	0.357
0	0	270	0	0.539	0.535	0.540

According to the result, it finds the average delay range of transmitting data from an Earth position to a position opposite on Earth is using about 0.765 seconds. For the average time of with Latitude or Longitude changes, it is 0.545 seconds for A*, 0.542 seconds for Dijkstra, and 0.639

seconds for the Orbit Base Path Algorithm. Therefore, the Dijkstra algorithm outperforms the others, and the A* algorithm has a close performance with the Dijkstra algorithm.

The findings from Table 4 indicate that latitude and longitude changes do not abruptly increase transmission delays. Instead, the delays exhibit a linear increase in proportion to the distance between two positions.

5. Conclusion

In conclusion, this project aims to analyze the issue of inter-satellite communication systems and simulate them to meet real-time system constraints. The current inter-satellite system cannot ensure the completion of data transmission within a specified timeframe. To address this, the project simulates communication between an LEO satellite, a ground station, and multiple satellites to evaluate communication capability and delay. The objective is to meet the deadline for downloading data from the LEO satellite.

The experiment results indicate that the path decision algorithm is a stable solution that meets the real-time system constraints. In contrast, the traditional LEO satellite data transmission method is prone to significant transition delay time variations due to longitude changes. This method results in unstable transmission delays and is incapable of ensuring data transmission completion within a specific timeframe. However, the path algorithm used in this project provides a stable transmission delay within a second, making it a reliable solution that meets real-time system constraints.

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