Inter-Satellite Routing Algorithms for Dual-Layer Low Earth Orbit Satellite Internet

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Abstract*—In recent years, low-cost low Earth orbit (LEO) satellites provide shorter-latency and higher-throughput services when compared to the medium Earth orbit (MEO) and geostationary Earth orbit (GEO) satellites. However, existing research on multi-layer satellite constellations and inter-layer routing typically focuses on larger-span constellations and routing among LEO/MEO/GEO. Research on the multi-layer LEO satellite networks is currently in its early stages. Existing routing algorithms designed so far have not fully leveraged the advantages of cross-layer links. Therefore, this paper proposes a method for establishing inter-layer links and rules for a dual-layer LEO satellite network, along with a routing algorithm for such a dual-layer constellation. Firstly, a uniform distribution dual-layer constellation configuration for LEO satellites is constructed, selecting the cross-layer linking satellites in LEOs. Secondly, to meet the requirement for long-term stable connections, a method for rapidly switching inter-layer links based on the periodic relative motion of satellites between layers is proposed, ensuring continuous and reliable transmission of inter-layer links within the satellite network. Furthermore, based on the rules for establishing inter-layer links and the dynamic relationships within the satellite network, time slot information for the dual-layer satellite network is established. Utilizing the Dijkstra's algorithm, the shortest transmission path from source to destination nodes in the dual-layer satellite network model is computed to determine the effective routing within the satellite network. Finally, a dual-layer constellation simulation model is built based on the parameters of the Kuiper constellation, and simulation experiments are conducted. Simulation results demonstrate that the dual-layer constellation routing algorithm (DCRA) reduces the round trip time (RTT) by 15.3%. At distance of 14,000 km between the source and the destination nodes, the average RTT is reduced by approximately 22.28% compared to the single-layer routing algorithm (SLRA).

***Index Terms*—Low Earth orbit (LEO), Dual-layer constellation, round trip time (RTT)**

I. Introduction

Nowadays, satellite networks play a vital role in the global communication systems by providing multiple broadband services and wide coverage for mobile users on the Earth [1], [2]. In recent years, with many new advanced techniques emerged, a mass of low Earth orbit (LEO) satellites have been launched, such as StartLink, OneWeb, etc., which provide shorter-latency and higher-throughput services, when compared to the medium Earth orbit (MEO) and geostationary Earth orbit (GEO) [3], [4]. However, single layer satellite networks still encounter several drawbacks, such as limited network capacity and coverage area for end-to-end communications [5]. In recent federal communications commission filings [6], SpaceX proposed and subsequently received permission to launch Starlink, a constellation of LEO satellites to provide low-latency, high-bitrate global Internet connectivity [7]. Researchers and operators have proposed the concept of a dual-layer LEO optical satellite network to seek flexible interaction. It consists of two LEO constellations at different altitudes, offering advantages such as strong data transmission capability, extensive inter-satellite path selection, multiple link replacement options, and high constellation flexibility [8], [9].

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In [10], the authors proposed an IP-based routing algorithm which was referred to as multi-layered satellite routing for a three-layered satellite network including GEO, MEO and LEO. In [11], the authors proposed a satellite grouping and routing protocol, which is suitable for a dual-layer satellite network consisting of MEO and LEO. In [12], the authors researched traffic control in dual-layer networks, focusing particularly on distributing packet flows between the two layers to minimize the transmission latency in the GEO and LEO network. In [13], the authors proposed a hierarchical satellite routing protocol on the basis of the satellite over satellite (SOS) layered satellite network structure. The SOS network comprises multiple layers of satellite constellations, including both GEO/MEO and LEO satellites. However, there is little research related to the routing algorithms and constellation for multi-layer LEO satellite networks.

Researchers first addressed the routing complexity in multi-layer LEO satellite networks by studying the inter-layer orbit-to-orbit link selection. In [14], the authors proposed an inter-layer communication algorithm tailored for Walker Delta constellations. In [15], the authors proposed an LEO satellite network consisting of K layers. They addressed inter-layer orbit-to-orbit links by introducing the concept of satellite logical positions, assuming each satellite can only communicate with adjacent satellites in the layers above and below. In [16], the authors designed an inter-layer links planning model for uninterrupted inter-layer communication in the dual-layer LEO constellation. Research on the cross-layer routing in large-scale LEO satellite networks is currently in its early stages. Existing routing algorithms designed so far have not fully leveraged the advantages of cross-layer links [17].

Therefore, this paper investigates the issue of cross-layer link selection to reduce the round trip time (RTT).

Firstly, we establish a dual-layer satellite network constellation configuration. To fully exploit the forwarding efficiency of the dual-layer satellite network, we draw inspiration from the GEO/LEO dual-layer satellite network constellation design approach. We establish a dual-layer LEO satellite network constellation where, unlike the GEO/LEO dual-layer satellite network constellation, the upper-layer constellation in the dual-layer LEO satellite network participates in forwarding business data tasks, serving as backup links to enhance the connectivity of the satellite network. The lower-layer constellation satellites are densely distributed to achieve full coverage of ground users. The upper-layer constellation satellites, on the other hand, are relatively sparse and do not provide direct transmission capability to the ground. Instead, they serve as backup links to provide rapid routing for data forwarding within the lower-layer satellite network.

Secondly, based on the link quality affecting business transmission capability and the number of forwarding nodes, we model and analyze inter-satellite orbits, cross-layer links, and node resources. This modeling includes decision variables such as the node buffer queue length, the number of path forwarding nodes, and the inter-layer link duration to construct the satellite network. We apply the Dijkstra's algorithm to compute the shortest paths between the source and destination nodes, ensuring the shortest RTT for optimal shortest path calculations.

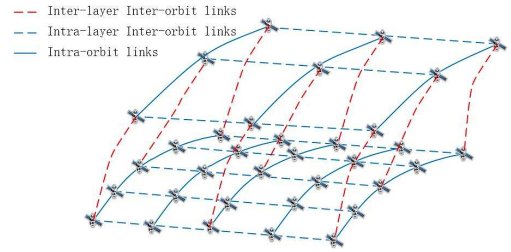


Fig. 1: Dual-layer constellation.

Lastly, using the Kuiper constellation orbits as an example, we construct a dual-layer LEO satellite network and apply Hypatia along with an improved path algorithm to simulate and verify the satellite network and routing algorithms. Simulation results demonstrate that the approach proposed in this paper can significantly reduce the RTT compared to the existing method.

The remainder of this paper is organized as follows. We discuss the dual-layer LEO network, and analyze the advantages of cross-layer transmission routing in Section II. In Section III, we describe the lifespan of inter-satellite links, the timing of inter-layer link switching in the model and the node buffer queue model, and then propose the dual-layer routing algorithm. Numerical results are provided in Section IV. Finally, conclusions are drawn in Section V.

II. Dual-Layer LEO Network

A. Dual-Layer Constellation Configuration

In a dual-layer LEO satellite network as shown in Fig. 1, according to the different altitudes of the satellites, the LEO satellite network is divided into a layer of lower LEO (LLEO) and a layer of upper LEO (ULEO). The satellite network is described as a network topology $G = (V, E)$, where $V = V_L \bigcup V_U$ denotes the set of satellites and consists of two subsets with $V_L = \{v_{L,1}, v_{L,2}, ..., v_{L,m}\}$ denoting the set of all LLEO satellites and $V_U = \{v_{U,1}, v_{U,2}, ..., v_{U,n}\}$ denoting the set of all LLEO satellites, respectively. Furthermore, $E = \{l_{L1,L2}, l_{U1,U2}, ..., l_{Lm,Un}\}$ denotes satellite links including the intra-orbit links, intra-layer inter-orbit links, and inter-layer inter-orbit links, where the link between satellite $v_{L,i}$ and satellite $v_{U,j}$ is denoted as $l_{Li,Uj}$.

From the point of view of an arbitrary satellite, two neighbors always remain in the same locations where the next one ahead on the same orbital plane, and the one behind on that orbital plane. The laser links to these neighbors only need to fine-tune their orientations, so these are the obvious candidates for the first two laser links. To form a network in the intra-layer, we also need to link between different orbital planes. Connecting satellite n on orbital plane p to satellite n on plane $p+1$ and also to satellite n on plane $p-1$ provides very good east-west connectivity.

When designing the dual-layer satellite constellation, it is crucial to consider factors such as the orbit design, the relative positions between satellites, and the interference and fading characteristics of communication links. In this paper we use the same constellation configuration to ensure consistent relative motion patterns between the upper and lower layer satellites. This is essential for maintaining stable inter-layer links because the relative positions between the satellites significantly affect the signal transmission and the link quality. Keeping both the upper and the lower layer satellites on the same orbital plane helps simplify the system design and management. It reduces the complexity required to communicate across different orbital planes and facilitates stable inter-layer communication links. The number of orbital planes for the lower layer satellites is assumed to be an integer multiple of the number of orbital planes for the upper layer sparse constellations. This integer multiple relationship aids in achieving a uniform distribution of satellites in the satellite communication network. This approach ensures a reasonable and even distribution of satellites covering the same regions in the inter-layer links. The dual-layer constellation depicted in Fig. 1 shows the upper-orbit satellites connected to the lower-orbit satellites within the same orbital plane. Due to the sparse distribution of the upper-orbit satellites, there is a relative motion between the satellites in the high and the low orbital planes. Therefore, borrowing from the concept of mobile phone cell handover, the lower-orbit satellites will perform channel switching with the two adjacent satellites to the upper-orbit satellite as their relative motion to ensure uninterrupted communication with the upper-orbit satellites.

B. Inter-Layer Link Switching

Inter-layer link switching refers to the process of managing and switching communication links established between satellites in space. This capability is crucial in satellite networks, especially in constellations where satellites move relative to each other or to ensure continuous communication coverage as satellites orbit the Earth. Inter-satellite link switching enables seamless handover between the upper and the lower orbit satellites to maintain connectivity, optimize data transmission, and ensure reliability throughout the satellite network. This functionality is essential for maintaining uninterrupted communication services, regardless of the movement or position of individual satellites within the constellation.

According to the aforementioned connection relationship in the previous section on the dual-layer satellite constellation, even the satellites within the same orbital plane experience relative motion. This causes the lengths of inter-layer links to vary over time, necessitating real-time switching based on the link quality and the satellite position information to ensure communication quality and connectivity. The switching process is analogous to the cell handovers in ground-based mobile networks, where the satellite control systems monitor and assess the status of different inter-layer links in real time. As depicted in Fig. 2, satellites A and C are adjacent ULEO satellites on the upper layer orbital plane, while satellite B is

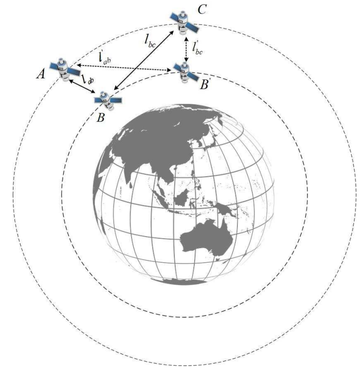


Fig. 2: Inter-layer link switching.

an LLEO satellite and $B^{'}$ is the virtual position node of B after relative motion has occurred on the lower layer orbital plane, with cross-layer links between upper and lower layer satellites. Initially, the cross-layer link l_{AB} between satellites A and B is shorter than the link l_{BC} between satellites C and B. Once it is determined that a new link (such as switching from l_{AB} to l_{BC}) offers better quality, the switching process is initiated.

Because the satellite relative motion is periodic and the orbital paths are predictable, the switching process can be precisely planned and executed, typically resulting in extremely short link disruption times, negligible (usually in the nanosecond range). Through appropriate switching strategies and real-time monitoring, high-quality connectivity of inter-layer links can be consistently maintained even amidst dynamically changing satellite orbits, effectively supporting complex satellite network applications and services.

C. Advantages of Cross-Layer Transmission

The total delay of data service in a satellite communication network is composed of several components: transmission delay, propagation delay, processing delay, and queuing delay. The transmission delay (or transfer delay) is the time required for a host or a router to send a data frame, calculated from the first bit sent to the completion of sending the last bit. It is given by

$$T_{Tran} = \frac{D_L}{S_t},$$

where D_L means the length of data frame and S_t means the speed of transmission. So the transmission delay is closely related to the data frame length and channel bandwidth. The propagation delay is the time it takes for an electromagnetic wave to travel a certain distance through the channel which can be calculated as

$$T_{Prop} = \frac{C_L}{S},$$

where C_L means the certain distance of channel and S means the speed of electromagnetic wave, which is closely related to the channel length of the link. The processing delay refers to the time a host or a router spends processing a packet upon receiving it. This includes tasks such as analyzing the

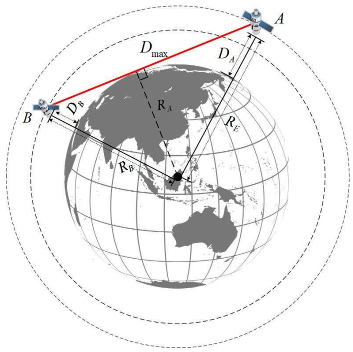


Fig. 3: The distance-max of inter-layer link.

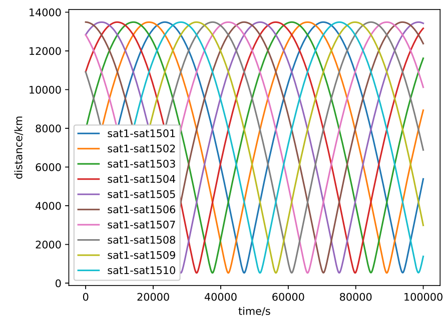


Fig. 4: The distance of inter-layer link.

packet header, extracting the data and checking the error, and determining the appropriate route. Finally, for the definition of the queuing delay, as packets traverse the network, they encounter multiple routers. After entering a router, the packets must wait in an input queue before processing. Once the router determines the forwarding interface, they then queue again in the output queue before being forwarded. In congested situations, the queuing delay can significantly contribute to the total delay.

In a large-scale dual-layer LEO satellite network, the selection of the inter-layer routing is primarily influenced by the transmission distance between the communication nodes, the number of nodes in the link, and the length of node queues. When the distance between the source and the destination nodes is short, the inter-layer communication delay is not necessarily shorter than the intra-layer communication delays due to the existence of dual-layer links. However, for a longer distance between the source and the destination nodes, the intra-layer transmissions require multiple satellite nodes for forwarding, resulting in a higher onboard processing times, which can reach up to 2ms according to the results in [7]. Routing via cross-layer links reduces the number of intermediate forwarding nodes, diversifies the data transmission paths, and decreases the node queue lengths. Consequently, this approach effectively reduces the RTT.

III. Dual-Layer Routing Algorithms

A. Inter-Layer Link Limits

In Fig. 3, the inter-layer link established by satellites A and B reaches the maximum laser communication distance $D_{\max}$. R_E is the radius of the Earth. D_A and D_B are the heights of the orbits, in which satellites A and B are located, respectively, and $D_{\max}$ is given by

$$D_{\max} = \sqrt{(R_E + R_A)^2 - R_E^2} + \sqrt{(R_E + R_B)^2 - R_E^2}.$$

At this time, the inter-layer link is exactly tangent to the Earth and is not obscured by the Earth. If the movement of the two satellites causes the inter-layer link distance to increase further, the inter-layer link will be blocked by the Earth and disconnected.

For the designed dual-layer satellite constellation, the lower layer linking satellites always establish the inter-satellite links with the nearest upper-layer satellite in the same orbit. Taking the dual-layer satellite constellation parameters in Tab.I as an example, where the number of lower-layer orbit is three times that of the upper-layer, so we select the lower-layer orbits numbered with K satisfying the condition of $\mod(K, 3) = 0$ as the linking orbit, where $\mod(,)$ denotes the modulo operation. Similarly, the number of lower-layer orbit satellites is five times that of the upper-layer orbit satellites, so we select the lower-layer node satellites numbered with N satisfying the condition of $\mod(N, 5) = 0$ as linking satellites.

We studied the variation of these linking satellites over time and their inter-satellite link distances with the upper-layer satellites. Fig. 4 shows the distances between the sta1 and the sat1501 sat1510 over time, where the sat1 means the first satellite of the first orbit in the lower layer, and the sat1501 to the sat1510 mean all of the satellites in the first orbit of the upper layer. As the linking satellite, the sat1 always establishes link with the shortest link from the sat1501 to the sat1510. According to the simulation results, the lower-layer linking satellites maintain stable inter-satellite links with the upper-layer satellites for a duration of 2,365 seconds. The inter-satellite link distances between the lower-layer linking satellites and the upper-layer satellites are no greater than 2,241 km, meeting the requirement for stable transmission of inter-satellite laser links [16].

B. Traffic Model Analysis

We assume that data packets arrive on the interstellar link at a rate ξ according to a Bernoulli process. The data packet transmission process on the interstellar link can be viewed as a G/G/1 queue [20], under the first-come-first-served rule, with an arrival rate of ξ. Assume the buffer size of the interstellar link is P. Let ζ_{ab}^t denote the buffer state of link l_{ab} at time slot t. When there are still $W(W < P)$ packets waiting for transmission in the buffer of interstellar link l_{ab}, the link is active with $\zeta_{ab}^t = W/P$; when the number of waiting packets in the buffer of interstellar link l_{ab} is greater than or equal to the buffer size, it is necessary to switch the link for transmission; otherwise, when the buffer is empty, $\zeta_{ab}^t = 0$.

To avoid link congestion, when the number of packets in the buffer of the interstellar link reaches the buffer size, the shortest path is recalculated and the link is switched, and when $\zeta_{ab}^{t} = 0$, the route switches back to the original link.

C. The Dual-Layer Constellation Route Algorithm

In this paper, to characterize the topology changes in a large-scale LEO satellite network, we utilize the time slot information to describe the connectivity of the inter-satellite links and the traffic transmission within these links during specific time slots. Concurrently, based on the path information and traffic control model computed from the previous time slot, we continuously update the lengths of the cache queues between the links in the route.

Moreover, for the selected source-destination node pairs, it is assumed that for each time slot, at least one connected path must exist in the satellite network to meet the requirement for network transmission. Using the time slot information to represent the satellite communication network, this paper employs the Dijkstra's algorithm to compute the data routing path. The flowchart of the algorithm is explained as Fig. 5.

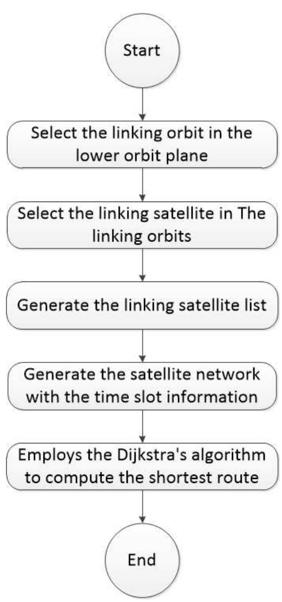


Fig. 5: The flowchart of the algorithm.

In summary, in order to realize low latency routing for the dual-layer LEO satellite network, a routing algorithm, referred to as the dual-layer constellation routing algorithm (DCRA), is designed in this paper with the detailed steps summarized in Algorithm 1 and explained as follows:

Algorithm 1 The Proposed DCRA

Require: Source node S, destination node D
Ensure: The shortest route of dual-layer constellation R
1: Select the lower orbit plane K satisfying $\mod (K, k) = 0$ as the linking orbit;
2: Select the satellite N satisfying $\mod (N, n) = 0$ in linking orbits as the linking satellite;
3: Generate the linking satellite list: linkingsatslist;
4: **for** i in linkingsatslist **do**
5:     **for** j is the upper-layer satellite of same orbit plane **do**
6:         Calculate the distance d_{ij};
7:     **end for**
8:     Select the shortest distance d_{ij};
9:     Establish the cross-layer links l_{ij};
10: **end for**
11: Generate the satellite network with the time slot information;
12: Employs the Dijkstra's algorithm to compute the shortest route;
13: **return** The shortest route of dual-layer constellation R

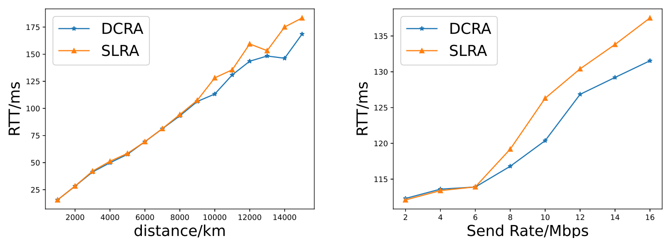
The first step is to establish the dual-layer inter-satellite links based on the constellation configuration. The lower-layer satellite network selects orbits numbered with K for $\mod (K, k) = 0$ as the dual-layer link orbits, where k indicates that the number of the lower-layer orbit planes is k times that of the upper-layer orbit planes. The second step is to select satellites numbered N in the lower-layer satellite network for $\mod (N, n) = 0$ as the cross-layer link satellites, where n means that the number of satellites in the lower-layer orbit plane is n times that in the upper-layer orbit plane. The third step is to construct a list of link-building satellites based on the selections in the first and second step. The fourth to the eleventh steps are to select the shortest inter-satellite link between the lower-layer orbit building satellites and the upper-layer orbit satellites based on the calculated link distances to establish the dual-layer links and generate the time slot information. Finally, the last step is to apply the Dijkstra's algorithm to obtain the shortest transmission path for that time slot.

IV. Numerical Results

To validate the feasibility and effectiveness of the proposed DCRA for large-scale dual-layer LEO satellite networks, this paper utilizes Python to create constellations, add links, and construct a dual-layer LEO satellite network scenario within the Hypatia satellite network simulation platform. Furthermore, the proposed DCRA is programmed within Hypatia for performance evaluation. In the simulation, the existence of caching queues at the forwarding nodes in the routing process is considered, with a processing delay of 2ms for node forwarding. The theoretical transmission time of a route is calculated as the sum of node processing time and link forwarding time. Using the theoretical transmission time of the route as the weight, the Dijkstras's algorithm is applied to find the shortest path between the source and destination, which is then compared with the single-layer routing algorithm (SLRA) in [18]. For a fair comparison, the parameters such as the altitude and orbit of the large-scale satellite network are referenced from the Kuiper constellation, and data traffic is generated at a constant bit rate. The experimental simulation parameters are set similar to those in [19], which are also shown in Tab. I.

TABLE I: Constellation Parameters

Constellation Type	Upper Layer	Lower Layer
Number of Satellites	100	1500
Altitude/km	1200	630
Inclination Degree/°	51.9	51.9
Period/hours	16.64	14.80
Orbit Planes	10	30
Number of Satellites per Orbit	10	50
Eccentricity	10^{-7}	10^{-7}



(a) RTT v.s. Src-dest distance

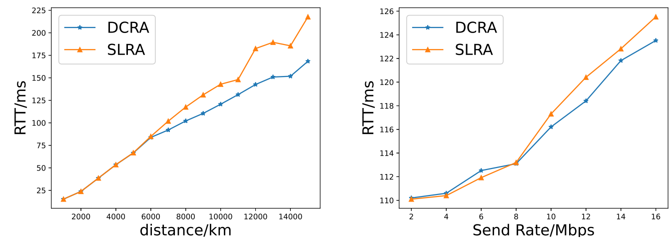
(b) RTT v.s. Data rate

Fig. 6: Performance comparison of RTT for the DCRA and the SLRA.

Fig. 6(a) depicts the RTT between the source and the destination nodes for the two routing algorithms at different distances. It can be seen that as the distance increases, the RTT for the two routing algorithms also increases. It can also be observed that compared to the proposed DCRA, the conventional SLRA exhibits slightly higher RTT when the distance is less than 8,000 km. This verifies that when the distance between source and destination nodes is relatively short, the delay of dual-layer communication is not necessarily better than that of single-layer communication. However, at distances greater than 8,000 km, the DCRA shows a smaller RTT. This is attributed to the use of cross-layer links in routing transmission, meeting the requirement for wide-area low-latency transmission. Additionally, the DCRA proposed in this study reduces the average RTT by approximately 19.7% compared to the SLRA when the distance between the source and destination nodes is 14,000 km.

Fig. 6(b) shows the variation in the RTT for different data transmission rates while maintaining the same source-destination , where we assume that the source is Tokyo and destination is Chicago and their distance is about 10,000km. It can be seen that the increase in the data transmission rate, there is an increase in the network traffic for both algorithms, leading to greater competition for node and channel resources. In particular, the DCRA uses the cross-layer inter-layer links in packet transmission, reducing the number of relay forwarding nodeswhen compared to the conventional SLRA, and such reduction in the node processing delay further reduces the RTT by 14.16%.

In addition, we also simulated a larger scale dual-layer LEO network with parameters shown in Tab. II. The RTT of both SLRA and DCRA at different data transmission rates



(a) RTT v.s. Src-dest distance

(b) RTT v.s. Data rate

Fig. 7: RTT of large scale dual-layer LEO network for the DCRA and the SLRA.

and distances between the source and destination nodes are depicted in Fig. 7. The results indicate that the DCRA reduces the RTT by 15.3% under node congestion condition. At distance of 14,000 km between the source and the destination nodes, the average RTT is reduced by approximately 22.28% compared to the SLRA.

TABLE II: Parameters of a Larger Scale Dual-Layer LEO Network

Constellation Type	Upper Layer	Lower Layer
Number of Satellites	400	3600
Altitude/km	1200	630
Inclination Degree/°	51.9	51.9
Period/hours	16.64	14.80
Orbit Planes	20	60
Number of Satellites per Orbit	20	60
Eccentricity	10^{-7}	10^{-7}

V. Conclusion

This paper focused on the multi-layer satellite constellations and inter-layer routing. In this paper, we addressed the challenges in data transmission within large-scale LEO satellite networks, such as high latency and low routing efficiency due to network dynamics and node scale. We proposed a solution by introducing a dual-layer LEO satellite network with inter-layer link establishment rules and methods. A routing algorithm, referred to as the DCRA, specialized for the dual-layer constellation LEO satellite networks was also proposed to enhance the transmission efficiency. The DCRA begins with the division of satellite orbits to construct a uniform-ly distributed dual-layer constellation LEO satellite network configuration. Furthermore, the DCRA adopts a method for rapid switching of cross-layer links based on the periodic relative motion of inter-layer satellites to ensure uninterrupted transmission across layers. Additionally, the DCRA obtains the time slot information for the dual-layer satellite network based on dynamic satellite relationship, and utilizes the Dijkstra's algorithm to compute the shortest transmission path within the dual-layer satellite network model. Finally, we varified the proposed DCRA by using a simulation model based on the parameters from the Kuiper constellation and conducting simulation experiments. Numerical results demonstrated that compared to the SLRA, the DCRA effectively reduces the RTT for large scale LEO satellite networks. Moreover, as the network scale increases, the efficiency of the proposed DCRA improves, highlighting its potential scalability and performance benefits.

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