High-Reliability, Low-Latency, and Load-Balancing Multipath Routing for LEO Satellite Networks

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***Abstract*—Being a critical part of the sixth generation mobile networks (6G) infrastructure, satellite networks have rapidly developed in recent years. With the increasing number of satellites and high mobility, the challenges of Ultra-Reliable and Low-Latency (URLL) services are increasingly prominent. The regular topology and orbital movement of low earth orbit (LEO) satellites present a new opportunity for the design of network routing for URLL services. In this paper, we propose a High-Reliability, Low-Latency, and Load-Balancing Multipath Routing (HLLMR) to support URLL services for LEO satellite networks. To ensure the reliability of satellite network transmission, a packet is transmitted through multiple paths. The path and link selection strategy avoids hotspots through load balancing to ensure end-to-end reliability and delay and minimize the link cost. Using the Starlink constellation, we illustrate the advantages of HLLMR routing in terms of delay and reliability.**

***Index Terms*—satellite networks, multipath routing, load balancing, LEO, end-to-end reliability**

I. INTRODUCTION

With the fast advance of satellite launch technology, the cost of satellite launch continues to decrease. Tens of thousands of satellites have made it possible to deliver real-time high-speed communication services over a wide area around the earth. LEO satellites have less transmission delay and higher transmission rates thanks to their lower near-Earth distances [1], [2]. LEO satellite networks have been developed by SpaceX, OneWeb, and Telesat, and investigated by many researchers [3]. The high mobility and large scale of LEO satellites, compared to medium earth orbit (MEO) and geostationary orbit (GEO) satellite networks, pose new challenges for routing algorithm design. How to achieve high reliability and low delay services in LEO inter-satellite routing is a key concern [4], [5].

The basic idea of the satellite network routing strategy is to divide the satellite network into time slices based on the satellite orbit scheduling and satellite position by period. The topology of the satellite network can be viewed as unchanged within a time slice [6]. Given the large number of LEO satellites moving along orbits regularly, there can be many options for path selections. Due to the uneven population around the earth, satellites near hotspots can have a much higher load, leading to longer delays [7], [8]. To solve the above problem, Zhang et al. [9] proposed a temporal centrality-balanced traffic management scheme, which aims to control network traffic to reduce network congestion. Li et al. [10] proposed state aware routing model to improve load balancing by dynamically adjusting queuing delay weights through link states. The above-mentioned works ensure reliability mainly with link layer retransmissions. However, due to the high dynamic and long-distance inter-satellite links, retransmission may not be effective in handling link outages while it will increase the latency substantially.

Given the growing demand for Ultra-Reliable and Low-Latency (URLL) services in 6G, the routing goal is to ensure the end-to-end reliability and reduce latency of packet transmission considering load balancing and link costs. The main contributions of the paper are three-fold. First, we propose a new multi-path routing approach for supporting Ultra-Reliable and Low-Latency (URLL) services in LEO satellite networks. The source satellite first determines the area of satellites that can relay the URLL packet, which construct a grid. The source can select part of the links in the grid to relay the packet. An optimal link selection problem is formulated, aiming to minimize the link cost under the end-to-end reliability and delay constraints. Second, a High-Reliability, Low-Latency, and Load-Balancing Multipath Routing algorithm is proposed based on the optimization problem. Third, extensive simulations have been conducted to investigate the performance of the proposed solution. Simulation results demonstrate that the proposed routing has superior performance in terms of average delay, and energy cost while being able to guarantee the reliability.

The rest of the paper is organized as follows, Sec. II presents the system model. The analytical end-to-end reliability is presented in Sec. III. The HLLMR protocol is described in Sec. IV. The performance evaluation of our proposed routing algorithm is given in Sec. V, followed by concluding remarks and future research issues in Sec. VI.

II. SYSTEM MODEL AND PRELIMINARY

A. System Model

Currently, there are many constructed constellations of LEO satellites. The distribution of satellites in the LEO satellite networks is regular and homogeneous. We analyze the LEO

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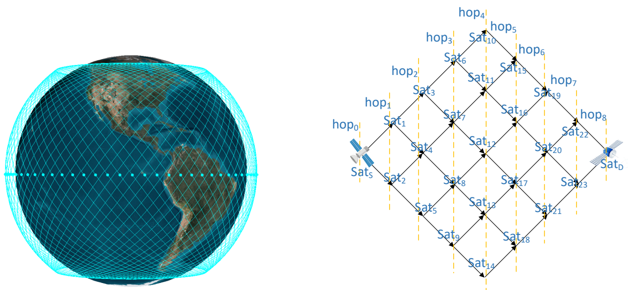
satellite networks model based on the Starlink constellation. The Starlink project is being built in several phases, and the current mature model is the first phase of the completed satellite constellation, which contains 72 orbital planes with 22 satellites per orbit, for a total of $1,584$ satellites. The orbits are 550 km above Earth [11], [12]. The network topology is shown in Fig. 1 (a).



(a) Network topology (b) Grid model

Fig. 1. Satellite network model

The LEO satellite network link can be represented by the graph $G = (V, E)$, where $V = \{S_1, S_2, ..., S_n\}$ denotes the set of satellites, and $E = \{L_{i,j}\}$ for $\{\text{i,j}\} \in [1, 2, ..., \text{n}]$ denotes the set of inter-satellite links. $L_{i,j}$ represents the link from satellite S_i to satellite S_j. According to the orbit distribution of the LEO satellite network, the link from the source satellite node to the destination satellite node can be represented as a grid model. As shown in Fig. 1 (b), the edges of the grid represent the inter-satellite links and the vertices represent the satellites.

As shown in Fig. 1 (b), there are multiple transmission paths from source node S to destination node D, and multiple satellites can be selected for each hop. To avoid long link layer retransmission delay, we can transmit packets through multipath to improve reliability. To ensure the smallest number of hops reach the destination, packets can only be forwarded in two directions towards the destination. Define h_i the set of satellites i-hop away from S. We define the end-to-end paths vector from the S to D as $path_S^D = \{L_{h_0}^{h_1}, L_{h_1}^{h_2}, ..., L_{h_{D-1}}^{h_D}\}$, $L_{h_i}^{h_{i+1}}$ is the links between h_i and h_{i+1}, different satellites in each hop set can be selected to transmit a packet, h_D is the last hop.

B. Problem Formulation

In this work, we focus on URLL services which should ensure end-to-end reliability and delay. For URLL packets, the goal is to minimize the packet transmission cost $Cost_S^D$ from the source node S to the destination node D on the basis of the guaranteed reliability. We can formally define the multipath routing problem for URLL services in satellite networks as finding the optimal end-to-end reliable transmission of packet streams with the objective of minimizing the transmission costs as follows:

$$\begin{aligned} &\text{minimize } Cost_S^D \\ &s.t.\ P_S^D > P_{path}^c \\ &Pb_{S_i}^{S_j} > Pb_{link}^c\ . \end{aligned} \tag{1}$$

End-to-end reliability P_S^D denotes the reliability of transmitting packets from source node S to destination node D. The link reliability $Pb_{S_i}^{S_j}$ can reflect the transmission utility of link $L_{i,j}$. Pb_{link}^c denotes the threshold value of link reliability. P_{path}^c denotes the threshold value of end-to-end reliability. The end-to-end cost consists of the link cost in each hop as follows:

$$Cost_S^D = \sum_{S_i \in h_k}^{S_j \in h_{k+1}} Cost_{S_i}^{S_j}, k \in [0, n], \tag{2}$$

where n denotes the total number of hops from the source node S to the destination node D. Inter-satellite transmission cost $Cost_{S_i}^{S_j}$ is given by the sum of the propagation delay cost $PD_{S_i}^{S_j}$ and the waiting cost $LD_{S_i}^{S_j}$ caused by different link loads as follows:

$$Cost_{S_i}^{S_j} = PD_{S_i}^{S_j} + LD_{S_i}^{S_j}. \tag{3}$$

$PD_{S_i}^{S_j}$ can be calculated by

$$PD_{S_i}^{S_j} = Dis_{S_i}^{S_j}/PS, \tag{4}$$

where $Dis_{S_i}^{S_j}$ denotes the distance from satellite S_i to satellite S_j and PS denotes the propagation speed of the signal in free space.

To calculate LD, $Hot = \{hot_1, hot_2, ..., hot_n\}$ denotes the set of hot regions, and n denotes the number of hot regions. Denote the region hot_i by $\{lon_w, lon_e, lat_n, lat_s\}$, where lon_w and lon_e are the longitudes corresponding to the west and east boundaries of the region, and lat_n and lat_s are the latitudes corresponding to the north and south boundaries of the region.

We can obtain the regional center latitude and longitude by $(lon_w + lon_e)/2$ and $(lat_n + lat_s)/2$ respectively. According to the distance $Dis_{S_j}^{hot}$ of the satellite S_j from the hot spot center, we define the waiting cost LD as follows:

$$LD_{S_i}^{S_j} = LB \times \overline{QD}, \tag{5}$$

where $LB = \exp(1/Dis_{S_j}^{hot})$ denotes the load balancing factor, and $\overline{QD}$ indicates the average waiting cost. The waiting cost is difficult to obtain in real time. Instead, here we use the average waiting cost $\overline{QD}$ according to the history data.

III. END-TO-END RELIABILITY CALCULATION

The satellite network with directional multipath routing is viewed as a directed graph, with no loops. Each link can deliver a packet successfully with a probability, named link reliability, which determines the end-to-end reliability. In this section, end-to-end reliability and link reliability are derived.

A. Link Reliability Calculation

Satellite networks rely on satellite links (SL) for packet transmissions. The main considerations for packet transmission in the channel are link attenuation and antenna gain. The satellite received power P_r is determined by the transmit power P_t, the antenna gain G, and the transmission loss L. The satellite received power P_r is defined in decibel form as:

$$P_r = P_t + G_t + G_r - L_{FS}, \tag{6}$$

where G_t denotes the antenna transmit gain, and G_r denotes the antenna receive gain. As the propagation loss is mainly caused by the free space loss, the loss is expressed as the free space loss $L_{FS} = 10\lg[(4\pi d)/\lambda]^2$, where λ denotes the signal operating wavelength, and d indicates the signal propagation distance. Antenna gain $G = \eta\left(\pi D/\lambda\right)^2$, where η is the antenna efficiency, and D denotes the diameter of the antenna.

The equivalent noise power at the receiving end of the satellite is as follows:

$$P_n = 10\lg(KT_P B_n), \tag{7}$$

where K is the Boltzmann constant, T_p is the thermodynamic temperature constant, and B_n is system noise bandwidth. Finally, we obtain the decibel representation of the signal-to-noise ratio of the satellite transmission signal $\mathrm{SNR} = \mathrm{P_r} - \mathrm{P_n}$.

The error probability of the $M-ary$ pulse position modulated system, when demodulated, is given by [13]:

$$P_e = \frac{(M-1)}{(\pi\mathrm{SNR})^2}\exp(-\mathrm{SNR}/4). \tag{8}$$

The bit error rate BER is given by

$$\mathrm{BER} = \frac{2^{\mathrm{k}-1}P_e}{2^{\mathrm{k}}-1}, \tag{9}$$

where $k = \log_2 M$. Link reliability $Pb_{S_i}^{S_j}$ is expressed by:

$$Pb_{S_i}^{S_j} = \exp(N\ln(1-\mathrm{BER})), \tag{10}$$

where N is the packet length.

B. End-to-End Reliability Calculation

As the satellite network is viewed as a grid network, packets have a well-defined number of hops to reach a certain vertex from the source satellite [14]. To calculate the end-to-end reliability, we apply a Markov process based analysis. From the source satellite, the vertices at different hop counts can be grouped into different sets of vertices $Ver = \{h_0, h_1, ..., h_D\}$, $h_i = \{S_1, S_2, ..., S_{N_i}\}$, where the satellites i-hop away from the source are in h_i. As shown in Fig. 1 (b), each h_i includes multiple vertices, where the vertices belonging to the same hop are denoted by h_i. After establishing the vertices sequence Ver, the end-to-end reliability can be calculated using Markov chains.

For a determined set of vertices h_i, since each satellite in the set may or may not successfully receive the tagged packet, we apply a binary number 0 to denote that the satellite did not receive the packet and the number 1 to denote that the satellite received the packet. So there are 2^{N_i} states denoting whether the satellites in h_i receive the packet or not, where N_i is the number of satellites in the set h_i. We denote the different states by $State_j^{h_i}$, where j denotes the j-th state of the vertex set h_i.

For instance, if h_i has three satellites, the 0-th (”000” in binary) state represents all three satellites final to receive the packet; and the 7-th (”111” in binary) state represents all three satellites receive the packet successfully.

$P(State_j^{h_i})$ denotes the probability of reaching state $State_j^{h_i}$. $Pb_{S_i}^{S_j}$ denotes the link reliability of $L_{i,j}$. Considering the set of inter-link nodes, the state transition probability from $State_j^{h_i}$ to $State_{j'}^{h_{i+1}}$ is denoted as $H_{j,j'}^{h_i}$.

Given the states in h_i, and the links between h_i and h_{i+1}, we can calculate the state probabilities of reaching state j' of h_{i+1} as follows:

$$P(State_{j'}^{h_{i+1}}) = \sum_{j=1}^{2^{N_i}-1} P(State_j^{h_i})H_{j,j'}^{h_i}, \tag{11}$$

$$H_{j,j'}^{h_i} = \prod_{S_l \in S_U^{h_i}}^{S_m \in S_U^{h_{i+1}}} Pb_{S_l}^{S_m} \times \prod_{S_k \in S_B^{h_i}}^{S_g \in S_B^{h_{i+1}}} (1 - Pb_{S_k}^{S_g}). \tag{12}$$

When h_{i+1} is in state $State_{j'}^{h_{i+1}}$, the satellite set $S_U^{h_{i+1}}$ denotes the satellite in the vertex set h_{i+1} that receives the packet successfully. The set of satellites $S_B^{h_{i+1}}$ denotes the satellites in the vertex set h_{i+1} for which the packet is not received. The satellite set $S_U^{h_i}$ denotes the satellite in the vertex set h_i that deliver packets to the satellites set $S_U^{h_{i+1}}$. The satellite set $S_B^{h_i}$ denotes the satellites in the vertex set h_i that do not deliver packets to the satellite set $S_U^{h_{i+1}}$. The end-to-end reliability from the source satellite S to the destination satellite D can be expressed as (13).

$$P_S^D = P(State_{j'}^{h_D}) = \sum_{j=1}^{2^{N_i}-1} P(State_j^{h_{D-1}})H_{j,j'}^{h_D} \tag{13}$$

IV. HIGH-RELIABILITY, LOW-LATENCY, AND LOAD-BALANCING MULTIPATH ROUTING

Here, we consider the situation that inter-satellite links of LEO networks are used as the backbone to deliver URLL packets globally. Satellite routing planning can be completed by the satellite which receives the URLL packets from the ground station. This satellite is named the source satellite. The satellite routing table only keeps $\{north, south, east, west\}$ four directional satellite addresses. The specific process of route selection has the following steps.

- **Step 1: Initialize packet transmission area.** When the ground station receives the packet, firstly, the ground station will identify the service satellite S that covers it. S is considered as the source satellite node in the LEO satellite network. Meanwhile, according to the location requested by the user, the satellite covering the destination ground station is denoted as D. Also the transmission area $Area_S^D$ can be determined according to S and D.
- **Step2: Initialize vertices set Ver.** Based on the location, we obtain get the satellite network packet transmission area $Area_S^D$. Based on the satellite orbits and the positions of the satellites in the area, we construct a grid

network with directional links. According to this grid, we can obtain the number of hops in the network. Also, we identify the vertex set corresponding to different hops $Ver = \{h_0, h_1, ..., h_D\}$.

- **Step3: Link cost $Cost_{S_i}^{S_j}$ and link reliability $Pb_{S_i}^{S_j}$ calculation.** After obtaining the set of hops based on the grid network, we can analyze the link reliability and costs. The corresponding $Cost_{S_i}^{S_j}$ and $Pb_{S_i}^{S_j}$ between different satellites of the transmission path can be calculated using (3) and (10), respectively.
- **Step4: Link selection.** There are two transmission directions for each satellite in the transmission area $Aera_S^D$, and the source satellite S can choose multiple link combinations to deliver packets to the destination satellite D. Our selection idea is to ensure that $Pb_{S_i}^{S_j} > Pb_{link}^c$ and $P_S^D > P_{path}^c$ on the basis of minimizing $Cost_S^D$, and to select two satellites per hop to transmit packets for higher reliability.

According to the design idea, we represent the HLLMR algorithm in pseudo-code as shown in Algorithm 1.

Algorithm 1: High-Reliability, Low-Latency, and Load-Balancing Multipath Routing

```
   Input: $S = \{lat_S, lon_S\}$, $D = \{lat_D, lon_D\}$
   Output: $path_S^D = \{L_{h_0}^{h_1}, L_{h_1}^{h_2}, \ldots, L_{h_{D-1}}^{h_D}\}$
1  Initialize $Area_S^D \leftarrow lat_S \leq lat \leq lat_D$,
     $lon_S \leq lon \leq lon_D$;
2  Initialize $Ver = \{h_0, h_1, \ldots, h_D\}$,
     $h_i = \{S_1, S_2, \ldots, S_{N_i}\}$;
3  Calculate $Cost_{S_i}^{S_j}$ and $Pb_{S_i}^{S_j}$ based on (3) and (10);
4  $h_i^{new} \leftarrow h_0$, i = 0;
5  for $h_i, h_{i+1} \in Ver$ do
6      for $S_i \in h_i$, $S_j \in h_{i+1}$ do
7          if $S_j == S_{hot}$ then
8              $j = j + 1$;
9          if $Pb_{S_i}^{S_j} > Pb_{link}^c$ and $Cost_{S_i}^{S_j} = \min(Cost_{S_i}^{S_j})$
            then
10             $h_{i+1}^{new} \leftarrow S_j$;
11         if $Pb_{S_i}^{S_{j+1}} > Pb_{link}^c$ and
            $Cost_{S_i}^{S_{j+1}} = \min(Cost_{S_i}^{S_{j+1}})$ then
12             $h_{i+1}^{new} \leftarrow S_{j+1}$;
13         $Ver_{new} \leftarrow h_{i+1}^{new}$;
14 Calculate $P_S^D$ based on (13);
15 if $P_S^D > P_{path}^c$ then
16     $path_S^D = \{L_{h_0}^{h_1}, L_{h_1}^{h_2}, \ldots, L_{h_{D-1}}^{h_D}\}$;
17 else
18     $Ver$ del $Ver_{new}$;
19     goto: step 5;
```

V. PERFORMANCE EVALUATIONS

To validate our proposed algorithm HLLMR, we simulated the constellation model based on the constellation parameters built in the first phase of Starlink. Our simulated constellation includes 72 orbits and 1584 satellites with an orbital altitude of 535 km [11]. We choose Victoria as the packet-originating location and Toronto as the packet-receiving location. We obtain the coordinates of the satellite to the ground point of the constellation at a certain moment through the simulation of the STK tool. With the algorithm, we can obtain the transmission area as shown in Fig. 2.

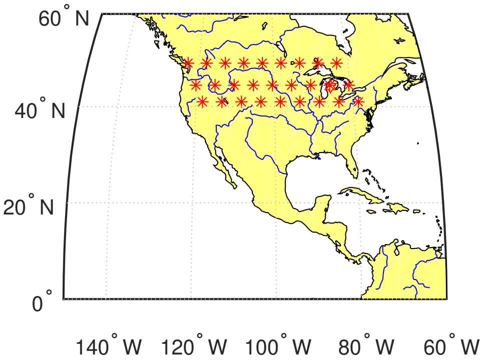


Fig. 2. Victoria to Toronto transmission area

As shown in Fig. 2, we can see that the transmission area from Victoria to Toronto is covered by 27 satellites. They can form a grid network with 3 rows and 9 columns. Through this grid network ground stations can choose multiple paths to deliver data from Victoria to Toronto. The center of the high-load area is in the Great Lakes region, marked by a hexagram on the map.

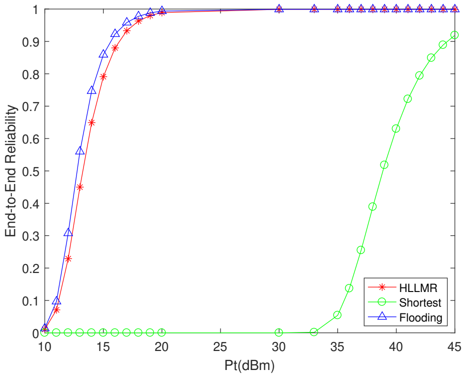


Fig. 3. End-to-end reliability curve with transmission power

The main parameters of the satellite signal include Bn = 2 GHz, f = 12 GHz, Gt/Gr = 45 dB. We analyze the performance of the proposed algorithm in three aspects: reliability, energy cost, and average delay. The energy cost is the product of the number of links selected by the routing algorithm and the per-link transmit power. We compare with the shortest-path and flooding routing algorithms. The shortest-path routing algorithm selects the single path with the minimum cost for packet transmission. The flooding algorithm is that all satellites in the transmission area forward packets.

As shown in Fig. 3, the shortest path routing algorithm performs poorly in end-to-end reliability when the transmit power is relatively small. Since the shortest path routing algorithm cannot avoid high-load links, it will lead to a reduction in link reliability. The HLLMR routing takes into account both cost and reliability to effectively avoid the high load situation in the path. Therefore, the reliability of our proposed algorithm HLLMR is close to that of Flooding, and it can be seen from Fig. 4 that HLLMR consumes much less energy because HLLMR selects fewer links to use.

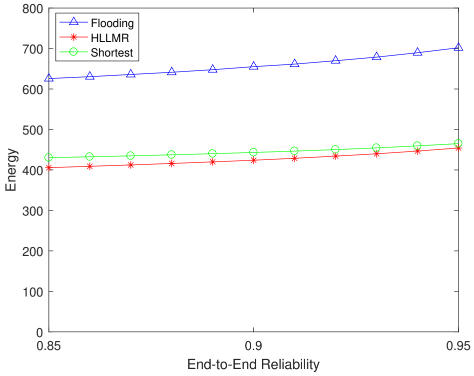


Fig. 4. Energy curve with end-to-end reliability

As shown in Fig. 5, the average delay performance of the HLLMR algorithm is similar to that of the flooding routing algorithm as the number of packets transmitted per second increases. The shortest path routing algorithm cannot effectively avoid the high load nodes which will greatly increase the transmission delay. Based on the above results and analysis, the effectiveness of our proposed routing algorithm is verified.

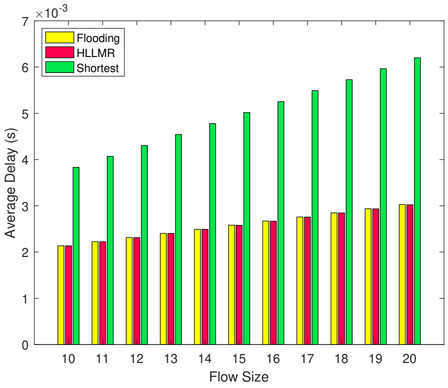


Fig. 5. Curve of average delay with the number of packets transmitted per second

VI. CONCLUSION

In this paper, we propose the High-Reliability, Low-Latency, and Load-Balancing Multipath Routing (HLLMR) algorithm for LEO satellite networks. We model the transmission area of the satellite network as a grid network through the orbital structure of the constellation. At the same time, as few satellites as possible are selected per hop to ensure reliability while reducing transmission redundancy. Through simulation and analysis, the reliability and delay of the HLLMR can achieve the delay and reliability performance close to the flooding routing strategy with a much lower cost.

As the services provided by LEO satellite networks are enriched, many new issues will arise. HLLMR addressed the problem caused by high link load due to the uneven distribution of users. In addition to uneven distribution of users, there are also problems with satellite equipment failures and link problems due to changes in the space environment. How to solve the link instability caused by the above conditions needs further research.

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