An Improved Minimum Hop Count Routing for LEO Mega-Constellations

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ABSTRACT

As the key technology of the sixth generation (6G) mobile communication network, low Earth orbit (LEO) satellites have the characteristics of low cost and low propagation delay. The new generation of LEO Mega-Constellations equipped with inter-satellite laser links (ISLL or ISL) can provide global High-speed network, and it can complement each other with the terrestrial network, thus facilitating the realization of the space-air-ground integrated network. Due to the large number of satellites in the LEO Mega-Constellations, the traditional centralized satellite routing algorithm is no longer suitable, so most of the LEO Mega-Constellations use distributed Minimum Hop Count Routing (MHCR) algorithm. In this paper, we propose an Improved Minimum Hop Count Routing (IMHCR) algorithm for LEO Mega-Constellations, which is based on the optimized LEO Mega-Constellations Network topology. NS2 simulation results show that compared with the MHCR, the proposed IMHCR algorithm can effectively reduce the number of hop and delay in the routing process.

CCS CONCEPTS

• **Networks** → Network algorithms; Network architectures; Network design principles.

KEYWORDS

Inter-Satellite Links, LEO Mega-Constellation, Minimum Count Routing algorithm, Satellite Network topology

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1 INTRODUCTION

The new generation LEO constellations equipped with inter-satellites links (ISL) are subverting the Satellite Internet business model [1, 2]. Compared with medium earth orbit satellites (MEO) and geostationary earth orbit satellites (GEO), low earth orbit satellites (LEO) have the advantages of low cost, low propagation delay, wide coverage, and larger communication capacity [3, 4]. LEO constellations are expected to supplement the ground network and achieve seamless global Internet coverage [5-7]. The earlier LEO constellation plans were represented by Iridium and Globalstar at the end of the 20th century, but they both ended in failure. In recent years, the LEO Mega-Constellations plans represented by the Starlink has once again promoted the business race of LEO satellite constellations globally, which has led to the launch of many LEO satellite constellation plans, such as Amazon's Kuiper, Oneweb, and Telesat. Compared with the LEO satellite constellations at the end of the 20th century, LEO Mega-Constellations in recent years have the characteristics of large number of satellites and can be equipped with inter-satellite links (ISL), so they are called LEO Mega-Constellations.

Routing algorithms, as one of the core technologies of satellite networks, have been already well researched. However, most current research focuses on Walker-Star constellations with a small number of satellites, such as Iridium, which mostly use centralized routing algorithms, with minimizing delay as the optimization goal. For the LEO Mega-Constellations that have emerged in recent years, such as Starlink, due to the extremely large number of satellites in the constellation, the computational cost and convergence time of routing required by the centralized routing algorithm will greatly increase, so it can no longer adapt well to the

LEO Mega-Constellation network. [8, 9] pointed out that in LEO Mega-Constellation routing, the number of hops should be the first indicator to be minimized rather than the sum of the link lengths of the path (or total propagation delay), because even though the transmission time can be ignored when using high ISL data rates, there is an on-board processing time (include queuing time) for data packets on the satellite. For laser links, the average on-board processing time can be several milliseconds, so the shorter total link length does not compensate for the cost of the extra hops. [9] proposed the DisCoRoute algorithm to arrange Inter-plane ISLs close to the polar regions, which can produce almost as good routing paths as the Dijkstra algorithm at a faster speed. [10] proposed the FROG algorithm, in which the ground station or terminal can choose the best peer satellite among the k nearest visible satellites, thereby reducing hop counts through the optimization of inbound and outbound hops. [11] proposed the Internet Fast Access Routing (IFAR) algorithm, which aims to quickly deliver user data packet to the ground core network, thereby avoiding multi-hop transmission on unstable inter-satellite links (ISL). [12] proposed the GomHop algorithm to find the best next hop for forwarding data packets in the connectionless network of a hybrid Mega-Constellation, by forwarding the data packet to the reachable orbit closest to the target node. The above-mentioned routing algorithms for the LEO Mega-Constellations all take the number of hops as the primary optimization goal, and are all implemented based on the distributed minimum hop count routing (MHCR) algorithm.

This paper proposes an improved minimum hop count routing (IMHCR) algorithm, which is implemented based on the improved Walker-Delta network topology. This algorithm further reduces the number of hops in the routing process by utilizing additional permanent inter-satellite links in Walker-Delta, that is, establishing more inter-satellite links. Experiments show that this algorithm can effectively reduce the hop count and delay in giant star routing.

The rest of paper is organized as follows. Part 2 presents the satellite network model. The proposed Improved Minimum Hop Count Routing algorithm is described in part 3. In part 4, we conduct a simulation on NS2 to compare IMHCR and MHCR algorithm. Finally, some conclusions are drawn in part 5.

2 SATELLITE NETWOR MODEL

2.1 LEO Mega-Constellations Structure

At present, most of the LEO Mega-constellations adopt the Walker-Delta type. Their orbital inclination angle is much less than 90°, and its range is generally between 50-70°. Their orbital planes are evenly distributed across the entire equator. Walker-Delta constellations can generally be expressed as:

$$\alpha : NPMP/NP/F, F \in \{0, ..., NP - 1\} \tag{1}$$

where α is the inclination angle of the constellation, N_P is the number of orbital planes, M_P is the number of satellites in each orbital plane, and F is the phasing factor of the Walker-Delta constellation. In addition, h is used to represent the height of the LEO Mega-constellations, but it does not affect the topology of the LEO Mega-constellations.

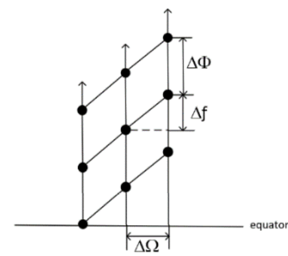


Figure 1: Parameters of Walker-Delta

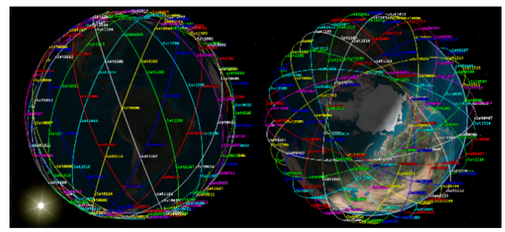


Figure 2: Three-dimensional topology of the Walker-Delta

As shown in Figure 1, the phase difference of two adjacent satellites in the same orbit $\Delta\Phi$ is:

$$\Delta\Phi = \frac{2\pi}{MP} \tag{2}$$

The phase difference of RANN (the longitude of the orbit's intersection with the equator from south to north) between adjacent orbits $\Delta\Omega$ is:

$$\Delta\Omega = \frac{2\pi}{NP} \tag{3}$$

The phase offsets of two adjacent satellites in two adjacent orbits Δf is:

$$\Delta f = \frac{2\pi F}{NPMP} \tag{4}$$

The three-dimensional topology of the Walker-Delta constellation is shown in Figure 2. It can be seen that the coverage of the Walker-Delta constellation does not include the polar regions.

2.2 Satellite period and coordinates

When the eccentricity of the earth is not considered, the period T of the satellite or constellation is:

$$T = 2\pi\sqrt{\frac{(r + h)^3}{GM}} \tag{5}$$

where r represents the radius of the earth, with a value of 6378.14km, G is the gravitational constant, with a value of 6.67×10^{-11}N.m^2/kg^2, and M is the mass of the earth, with a value of 5.965×10^{24}kg.

For any satellite in the Walker-Delta constellation, according to the constellation configuration, the in-orbit phase P_0 in its initial state (the angle from RANN to the initial position of the satellite along the moving direction of satellite) and the initial longitude of the satellite Lon_0 can be easily calculated. After any time t, the phase offset in the orbit ΔP, latitude Lan, the longitude difference

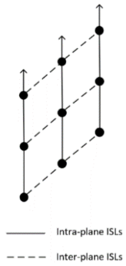


Figure 3: Two types of ISLs

ΔLon of satellite and the geographical coordinates $(0, 0)$, longitude Lon, and coordinate S can be expressed as:

$$\Delta P = (\frac{t\%T}{T}) \cdot 2\pi \tag{6}$$

$$Lan = \arcsin(\sin\alpha \cdot \sin((P0 + \Delta P)\%(2\pi))) \tag{7}$$

$$\begin{gathered}\Delta Lon = Lon0 + \arctan(\cos\alpha \cdot \tan \\ ((P0 + \Delta P)\%(2\pi))), Lon0 \in [-\pi, \pi]\end{gathered} \tag{8}$$

$$Lon = \begin{cases}\Delta Lon, \Delta Lon \in [0, \pi] \\ \Delta Lon - 2\pi, \Delta Lon \in (\pi, 2\pi]\end{cases} \tag{9}$$

$$S : (Lat, Lon) \tag{10}$$

2.3 ISL Length

In the Walker-Delta constellation, the length of the intra-plane ISL L_{Intra} remains unchanged, as follows:

$$LIntra = 2(r + h)\sin\frac{\Delta\Phi}{2} = 2(r + h)\sin\frac{\pi}{MP} \tag{11}$$

The length of Inter-plane ISL L_{Inter} will change with time, which is determined by the angle between the two satellites relative to the center of the earth Φ_{Inter}. Given the initial geographical coordinates of the two satellites: $S_1 : (Lat_1, Lon_1), S_2 : (Lat_2, Lon_2)$, the formula is as follows:

$$\begin{gathered}\Phi Inter = \arccos \\ (\sin Lat1 \cdot \sin Lat2 + \cos Lat1 \cdot \cos Lat2 \cdot \cos(Lon1 - Lon2))\end{gathered} \tag{12}$$

$$LInter = 2(r + h)\sin\frac{\Phi Inter}{2} \tag{13}$$

In the routing algorithm used in this article, we normalize the link length, which means using the average length of the ISL to represent the cost of a hop in the constellation.

2.4 Walker-Delta network topology in Grid mode

Currently, most of the ISL connection modes used in LEO constellations are Grid mode [13]. In this mode, a satellite establishes two intra-plane ISLs with two adjacent satellites in the same plane, and establishes two inter-plane ISLs with two adjacent planes. As shown in Figure 3 below, the solid lines represent intra-plane ISLs, and the dotted lines represent inter-plane ISLs.

On this basis, the overall topology of the Walker-Delta constellation is similar to a Manhattan Street network, as shown in the Figure 4 below, its constellation parameters are 70°: 100/10/0. In the algorithm description and simulation cases in this article F=0 is selected, when the constellation coherence is the strongest [8]. The coordinates of the satellite are expressed as (plane number, satellite number in plane).

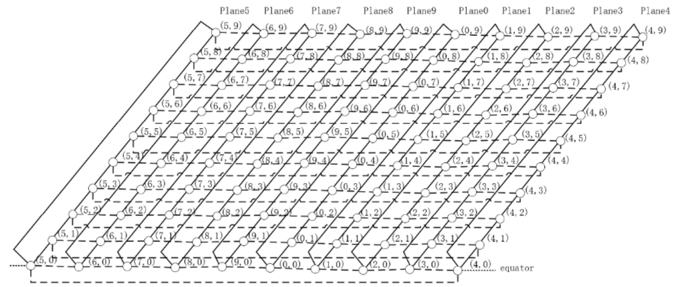


Figure 4: Overall topology of the Walker-Delta constellation in Grid mode

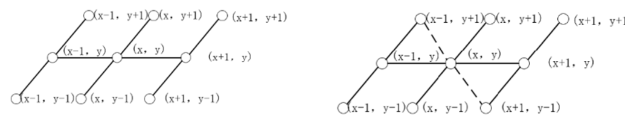


Figure 5: Potentially permanent Inter-plane ISLs in the Walker-Delta constellation

2.5 Optimized Walker-Delta constellation network topology

Werner [14] pointed out that in the Walker-Delta constellation, in addition to the ISLs of Grid mode, there are more potentially permanent Inter-plane ISLs. As shown in the Figure 5 below, they are represented by dotted lines.

We named the ISLs mode proposed by Werner *the Werner-6-ISLs mode*. Compared with the Grid mode, it has two more Inter-plane ISLs.

Given the Walker-Delta constellation 70°: 100/10/0, after using the Werner-6-ISLs mode, the constellation's intra-plane ISLs topology and inter-plane ISLs topology are show in Figure 6 and Figure 7 below.

The incomplete topology without considering the ISLs at the boundary is shown in Figure 8.

We make a partial comparison between Grid mode and Werner-6-ISLs mode. As shown in the Figure 9, from satellite $(9, 1)$ to satellite $(1, 9)$, Grid mode requires 4 hops (2 Inter-plane ISLs and 2 Intra-plane ISLs), while Werner-6-ISLs mode only requires 2 hops (2 Inter-plane ISLs). It can be concluded that the latter can reduce the hops of Intra-plane ISLs in routing process by adding more Inter-plane ISLs.

2.6 Inter-satellite visibility analysis

In the simulation, the constellation we use is Starlink shell1, its parameters are 53°:1584/72/0, and the altitude is 550km. We need to conduct visibility analysis based on Werner-6-ISLs mode. Only when corresponding ISLs can be established permanently, can we analyze the routing algorithm based on it. [15] pointed out that the condition for establishing a permanent ISL between two satellites

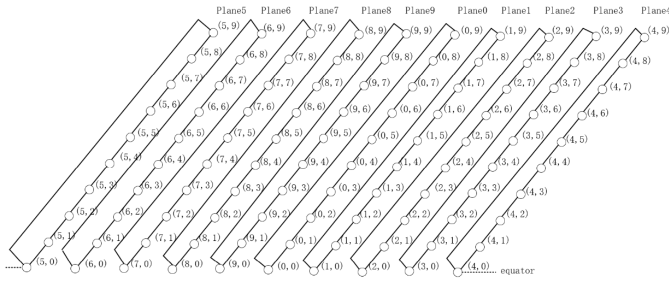


Figure 6: Intra-plane ISLs topology in Werner-6-ISLs mode

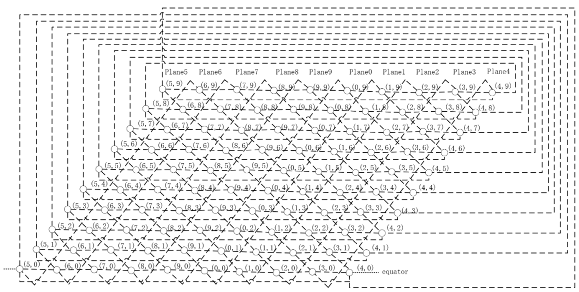


Figure 7: Inter-plane ISLs topology in Werner-6-ISLs mode

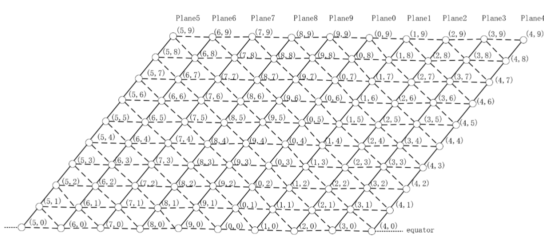


Figure 8: Incomplete topology without considering the ISLs at the boundary in Werner-6-ISLs mode

is that their AER (A: Azimuth, E: Elevation, R: Range) results are periodic and continuous. Due to the high degree of regularity and symmetry of LEO constellations, visibility analysis of one satellite can be extended to the satellites of entire constellation. Taking satellite (0, 0) as an example, in Werner-6-ISLs mode, it will establish ISL with (0, 1), (0, 21), (1, 0), (1, 21), (71, 0), (71, 1). The links established with (1, 21), (71, 1) are not available in Grid mode. We only need to perform AER analysis on these two links. The AER analysis results of these two links in STK are shown in Figure 10 and Figure 11.

It can be seen that in the Werner-6-ISLs mode, the ISLs are permanent ISLs, and the network topology of the Walker-Delta constellation is stable and will not change.

3 IMPROVED MINIMUM HOP COUNT ROUTING ALGORITHM

3.1 Minimum Hop Routing algorithm in Grid mode

At present, the distributed routing algorithm for LEO Mega-constellations is mainly the minimum hop count routing (MHCR) algorithm, which abstracts the constellation network topology into a Manhattan Street network based on the Grid mode. For any satellite S in the LEO Mega-Constellation, its coordinate is:

$$S:(PS,SS), PS\in\{0,\ldots,NP-1\} and SS\in\{0,\ldots,MP-1\} \quad (14)$$

where P_S represents the plane number where the satellite is located, S_S represents the satellite number in the plane, and the ranges of P_S and S_S both start from 0. Given any two satellites $S_1:(P_{S_1},S_{S_1})$, $S_2:(P_{S_2},S_{S_2})$, the minimum hop count number $minHop$ between them is determined by the coordinate difference, as follows:

$$\begin{aligned} minHop &= minHopInter + minHopIntra \\ &= min\{|PS2-PS1|, NP-|PS2-PS1|\} \\ &\quad + min\{|SS2-SS1|, MP-|SS2-SS1|\} \end{aligned} \quad (15)$$

where $minHop_{Inter}$ represents the number of Inter-plane ISLs required in any minimum-hop routing path, $minHop_{Intra}$ represents the number of Intra-plane ISLs required in any minimum-hop routing path, and there may be multiple minimum-hop routing paths.

The following begins to introduce the principle of the improved minimum hop count routing algorithm (IMHCR).

3.2 Prerequisite experience

The improved minimum hop count routing algorithm is implemented based on the Werner-6-ISLs mode, which uses additional Inter-plane ISLs to reduce the hops during the routing process.

First, some intuitive experiences based on Werner-6-ISLs mode are given, as shown in Figure 12.

Starting from satellite $\mathrm{Dst}:(\mathrm{P_{Dst}},\mathrm{S_{Dst}})$, after passing through two Inter-plane ISLs along the direction in which the plane number increases, the number range of satellites on the destination plane that can be reached is $[\mathrm{S_{Dst}}-2,\mathrm{S_{Dst}}]$. Considering that the satellite number on a plane will not decrease infinitely, starting from any satellite $\mathrm{S}:(\mathrm{P_S},\mathrm{S_S})$, after passing through n $(0 < n < N_P)$ Inter-plane ISLs along the direction in which the plane number increases, the number range of satellites on the destination plane that can be

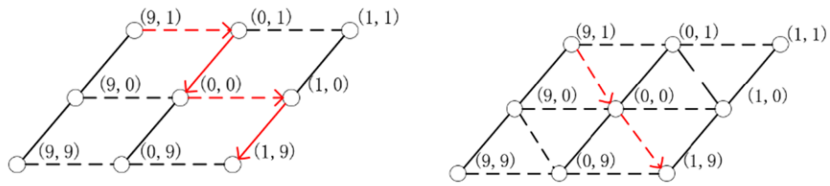


Figure 9: Partial comparison between Grid mode and Werner-6-ISLs mode

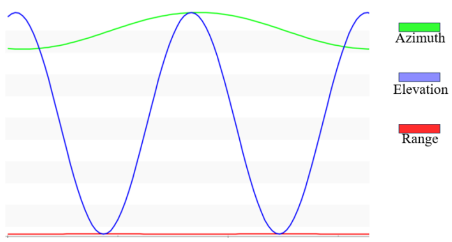


Figure 10: AER between (0, 0) and (1, 21)

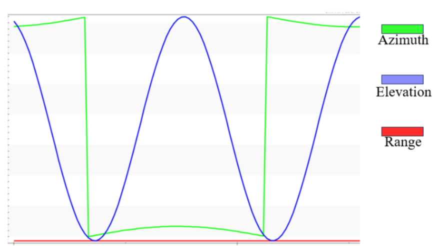


Figure 11: AER between (0, 0) and (71, 1)

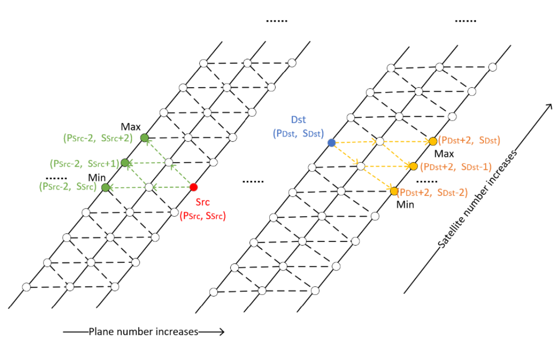


Figure 12: Intuitive experiences based on Werner-6-ISLs mode

reached *Range* can be expressed as:

$$Range = \begin{cases} [Ss-n, Ss], & 0 < n < Mp-1 \; and \; Ss-n >= 0 \\ [0, Ss] \cup [Ss-n+Mp, Mp-1], & 0 < n < Mp-1 \; and \; Ss-n < 0 \\ [0, Mp-1], & n >= Mp-1 \end{cases} \tag{16}$$

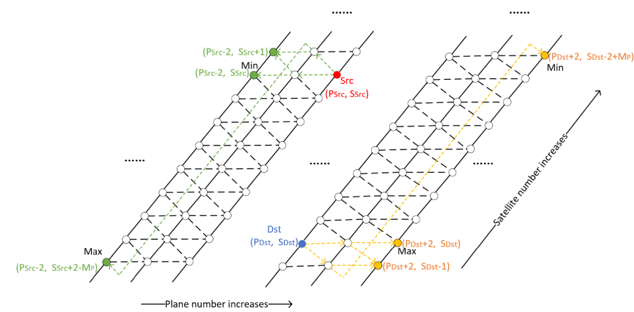


Figure 13: Normalize the value of Min and Max

When $0 < \mathrm{n} < \mathrm{M_P} - 1$, we take $\mathrm{Max} = \mathrm{S_S}$, $\mathrm{Min} = \mathrm{S_S} - \mathrm{n}$. When $\mathrm{Min} < 0$, $Min > Max$ will appear after normalizing *Min*, as shown in Figure 13.

Starting from the satellite Src : $(\mathrm{P_{Src}}, \mathrm{S_{Src}})$, after passing through two inter-plane ISLs in the direction in which the plane number decreases, the number range of the satellites on the destination plane that can be reached is $[\mathrm{S_{Src}}, \mathrm{S_{Src}} + 2]$. Considering that the number of satellites on a plane will not increase infinitely, starting from any satellite S : $(\mathrm{P_S}, \mathrm{S_S})$, after passing through n $(0 < \mathrm{n} < N_P)$ Inter-plane ISLs along the direction in which the plane number decreases, the number range of satellites on the destination plane that can be reached *Range* can be expressed as:

$$Range = \begin{cases} [Ss, Ss+n], & 0 < n < Mp-1 \; and \; Ss+n <= Mp-1 \\ [0, Ss+n-Mp] \cup [Ss, Mp-1], & 0 < n < Mp-1 \; and \; Ss+n > Mp-1 \\ [0, Mp-1], & n >= Mp-1 \end{cases} \tag{17}$$

When $0 < n < Mp - 1$, we take $Min = S_S$, $Max = S_S + n$. When $Max > Mp - 1$, $\mathrm{Max} < \mathrm{Min}$ will appear after normalizing *Max*, as shown in the Figure 13.

3.3 IMHCR Algorithm

The improved minimum hop count routing algorithm, like the minimum hop count routing algorithm, is a fully distributed routing algorithm. When a data packet arrives at a satellite, its next-hop forwarding address is completely determined by the address of the current satellite S : $(\mathrm{P_S}, \mathrm{S_S})$ and the address of the destination satellite *Dst* : (P_{Dst}, S_{Dst}). The calculation of the minimum hop route is divided into the following three situations: a) S and Dst are in the same plane, $\mathrm{P_S} = \mathrm{P_{Dst}}$ and $\mathrm{S_S} \neq \mathrm{S_{Dst}}$; b) *S* and *Dst* are in different planes, but they have the same satellite number, $\mathrm{P_S} \neq$

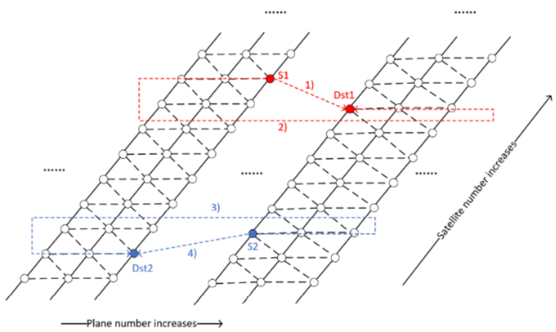


Figure 14: Four situations of situation c)

$P_{Dst}$and$S_S = S_{Dst}$; c) S and Dst are in different planes, and they have different satellite number, $P_S \neq P_{Dst}$and$S_S \neq S_{Dst}$.

For situation a) and situation b), the calculation method of IMHCR is same as the MHCR algorithm in Grid mode, it can be expressed as:

$$\begin{aligned} minHop = \\ min\{|SDst - SS|, MP - |SDst - SS|\} \\ +min\{|PDst - PS|, NP - |PDst - PS|\} \\ = \begin{cases} min\{|SDst - SS|, MP - |SDst - SS|\}, situationa \\ min\{|PDst - PS|, NP - |PDst - PS|\}, situationb \end{cases} \end{aligned} \quad (18)$$

For situation c), the IMHCR algorithm is quite different from MHCR algorithm in Grid mode. The general principles are: A) From the current satellite to the destination satellite, data packets can be forwarded in two directions, one is the direction in which plane number increases, the other one is the direction in which plane number decreases; when forwarding along the former direction, which is also from west to east, the minimum number of hops is $\mathrm{minHop}_{W \to E}$, and conversely, the minimum number of hops when forwarding along the latter direction is $\mathrm{minHop}_{E \to W}$. Finally, select the direction with the smallest number of hops. The $\mathrm{minHop} = \mathrm{minminHop}_{W \to E}, \mathrm{minHop}_{E \to W}$; B) No matter which direction will be chosen, it must be ensured that when the data packet reaches the plane of the destination satellite, it has the minimum in-orbit hop difference from the destination satellite.

In the IMHCR algorithm, the forwarding of packet is mainly determined by the plane number difference ΔP and satellite number difference ΔS between the destination satellite Dst and the current satellite S, which can be expressed as:

$$\Delta P = PDst - PS \quad (19)$$

$$\Delta S = SDst - SS \quad (20)$$

According to the positivity and negativity properties of ΔP and the direction of routing, situation c) can be divided into the following four situations: 1) $\Delta P > 0$, forwarding packet along the direction in which plane number increases; 2) $\Delta P > 0$, forwarding packet along the direction in which plane number decreases; 3) $\Delta P < 0$, forwarding packet along the direction in which plane number increases; 4)$\Delta P < 0$, forwarding packet along the direction in which plane number decreases. These situations are shown in Figure 14.

Situation 1) is analyzed in detail below, and the principles of cases 2, 3 and 4 are similar to 1 and will be omitted. At this time, $\Delta P > 0$ and packet will be forwarded along the direction in which plane number increases.

When $\Delta P \geq M_P - 1$, as shown in Figure 15, from current satellite to any satellite in orbit of the destination satellite, only need to using ΔP Inter-plane ISLs, and no Intra-plane ISL is needed. Because$\Delta S \neq 0$ at this time, the next hop should be forwarded along the Inter-plane ISL which will reduce satellite number. At this time $minHop_{W \to E} = \Delta P, nextHop_{W \to E} = (P_S + 1, S_S - 1)$.

When $\Delta P \langle M_P - 1, \Delta S \rangle 0, \mathrm{Min} = S_S - \Delta P \geq 0$, as shown in the Figure 16. In order to minimize the number of Intra-plane hops when packet reaches the plane of the destination satellite, it is necessary to consider the direction when forwarding in the destination plane. The number of hops from Max to Dst along the direction in which the satellite number increases is $H_1 = S_{Dst} - S_S = \Delta S$, and the number of hops from Min to Dst along the direction in which the satellite number decreases is $H_2 = M_P - \Delta P - H_1 = M_P - \Delta P - \Delta S$. If $H_1 \leq H_2$, such as $Dst1$, then the next hop should be forwarded along the Inter-plane ISL which not change satellite number, at this time $minHop_{W \to E} = \Delta P + \Delta S, nextHop_{W \to E} = (P_S + 1, S_S)$; conversely, if $H_1 > H_2$, such as $Dst2$, then the next hop should be forwarded along the Inter-plane ISL which will decreases satellite number, at this time $minHop_{W \to E} = M_P - \Delta S, nextHop_{W \to E} = (P_S + 1, S_S - 1)$.

When $\Delta P \langle M_P - 1, \Delta S \rangle 0, \mathrm{Min} = S_S - \Delta P < 0$, after normalization, $\mathrm{Min} = S_S - \Delta P + M_P > \mathrm{Max} = S_S$, as shown in the Figure 17. If $S_{Dst} \geq \mathrm{Min}$, only Inter-plane ISLs are needed to reach the destination satellite, such as $Dst3$, because$\Delta S \neq 0$, the next hop should be forwarded along the Inter-plane ISL which will decreases satellite number, at this time $minHop_{W \to E} = \Delta P, nextHop_{W \to E} = (P_S + 1, S_S - 1)$; if $S_{Dst} < \mathrm{Min}$, it is same as situation 2) above, such as $Dst1$, $Dst2$.

When $\Delta P < M_P - 1, \Delta S < 0, \Delta P \geq -\Delta S$, as shown in Figure 18. OnlyΔP Inter-plane ISLs are needed to reach the destination satellite. Because $\Delta S \neq 0$, the next hop should be forwarded along the Inter-plane ISL which will decreases satellite number, at this time $minHop_{W \to E} = \Delta P, nextHop_{W \to E} = (P_S + 1, S_S - 1)$.

When $\Delta P < M_P - 1, \Delta S < 0, \Delta P < -\Delta S$, as shown in Figure 19, it is similar to situation 2) above. The number of hops from Min to Dst along the direction in which satellite number decreases is $H_1 = \mathrm{Min} - S_{Dst} = -\Delta S - \Delta P$, and the number of hops from Max to Dst along the direction in which satellite number increases is $H_2 = M_P - \Delta P - H_1 = M_P + \Delta S$. If $H_1 \leq H_2$, such as Dst1, then the next hop should be forwarded along the Inter-plane ISL which will decreases satellite number, at this time $minHop_{W \to E} = -\Delta S, nextHop_{W \to E} = (P_S + 1, S_S - 1)$; conversely, if $H_1 > H_2$, such as Dst2, then the next hop should be forwarded along the Inter-plane ISL which will not change satellite number, at this time $minHop_{W \to E} = \Delta P + M_P + \Delta S, nextHop_{W \to E} = (P_S + 1, S_S)$.

Above is the method for calculating the minimum hop count $\mathrm{minHop}_{W \to E}$ and the next hop $\mathrm{nextHop}_{W \to E}$ when $\Delta P > 0$ and forwarding packet along the direction in which plane number increases. The flow chart is shown in Figure 20 below.

When$\Delta P > 0$, the method for calculating $\mathrm{minHop}_{E \to W}$ and $\mathrm{nextHop}_{E \to W}$ is similar to the method for calculating $minHop_{W \to E}$ and $nextHop_{W \to E}$. In the same way, when$\Delta P < 0$, these four data

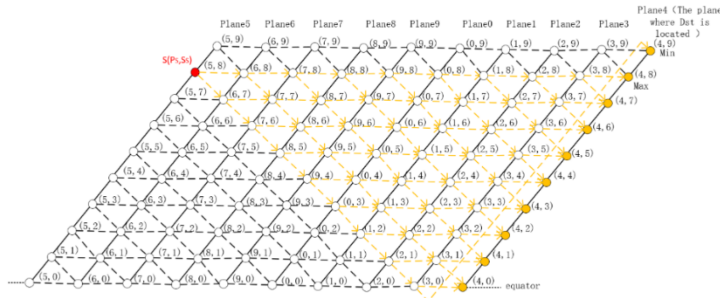


Figure 15: $\Delta P \geq M_P$ - 1

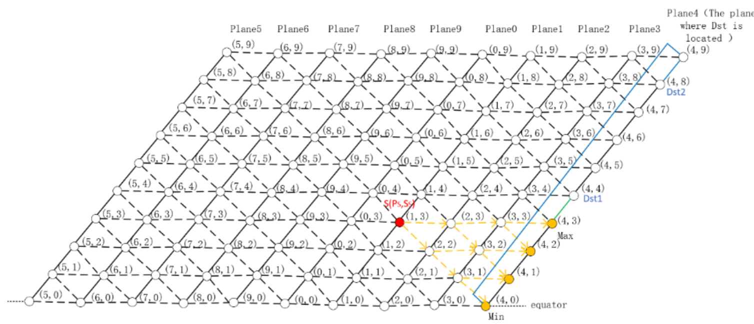


Figure 16: $\Delta P < M_P - 1$, $\Delta S > 0$, Min ≥ 0

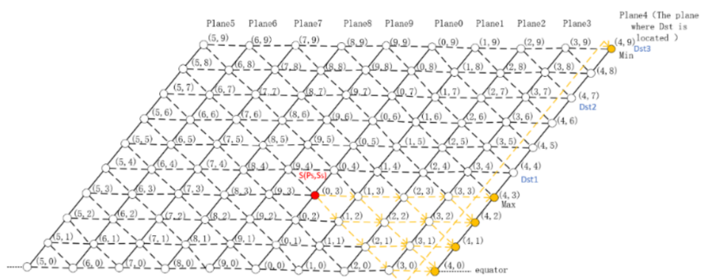


Figure 17: $\Delta P < M_P - 1$, $\Delta S > 0$, Min < 0

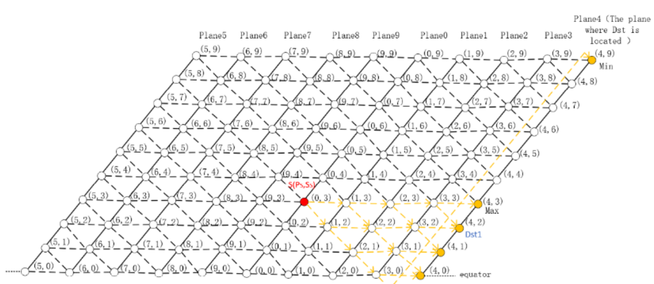


Figure 18: $\Delta P < M_P - 1$, $\Delta S < 0$, $\Delta P \geq - \Delta S$

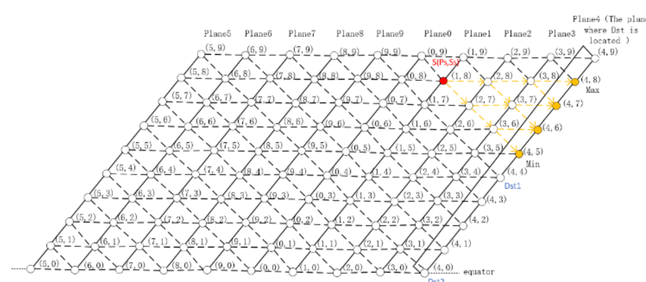


Figure 19: $\Delta P < M_P - 1$, $\Delta S < 0$, $\Delta P < - \Delta S$

can be calculated easily. Then for any $\Delta P \neq 0$, the minHop and nextHop can be expressed as:

$$minHop = \{minHopW \rightarrow E, minHopE \rightarrow W\} \tag{21}$$

$$nextHop = \begin{cases} nextHopW \rightarrow E, minHop = minHopW \rightarrow E \\ nextHopE \rightarrow W, minHop = minHopE \rightarrow W \end{cases} \tag{22}$$

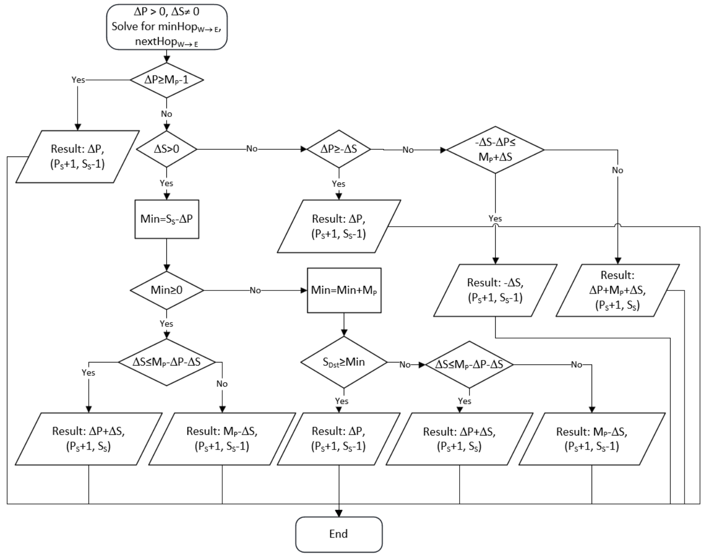


Figure 20: ΔP > 0, routing from West to East

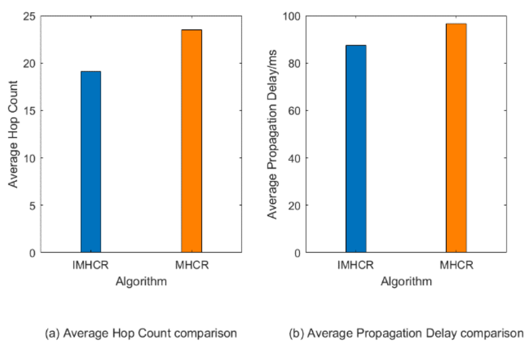


Figure 21: Comparison of overall hop count and propagation delay

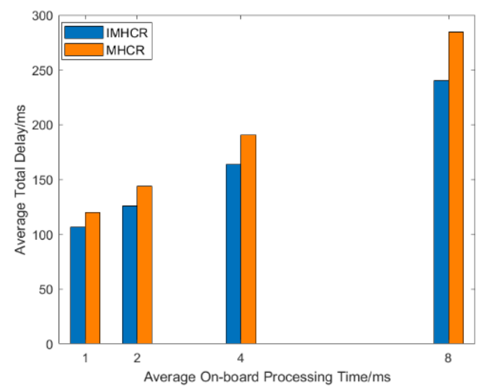


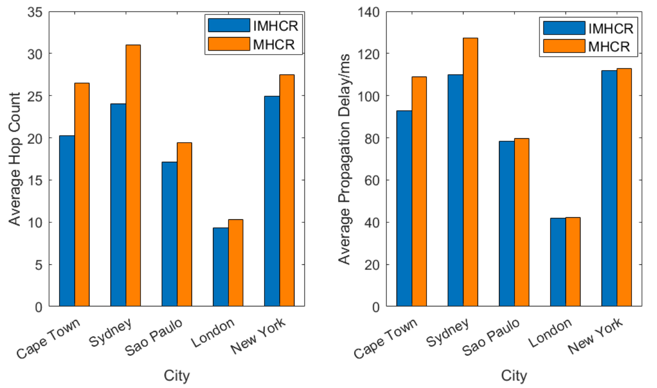
Figure 22: Comparison of overall total-delay

4 SIMULATION

In NS2, we built the constellation of Starlink Shell1, and its parameters are 53°: 1584/72/0, 550km. First, we analyze the overall performance of the improved minimum hop count routing algorithm (IMHCR) based on Werner-6-ISLs Mode and the minimum hop count routing algorithm based on Grid Mode. We send a data packet from one satellite to all other satellites. The average hop count and propagation delay of IMHCR and MHCR are shown in Figure 21. Compared with MHCR, the average number of hops of IMHCR is reduced by 18.63%, and the average propagation delay is reduced by 9.5%.

After taking on-board processing time into account, which takes 1, 2, 4 and 8ms as value, the average total delay of IMHCR and MHCR are shown in Figure 22. It can be seen that as the average on-board processing time increases, the performance of IMHCR will gradually increase compared to MHCR.

In addition, we also conducted the end-to-end delay comparison experiment on the ground. We send packets from Beijing (39.6°N, 116.2°E), and take Cape Town (34.0°S, 18.0°E), Sydney (33.8°S, 151.2°E), Sao Paulo (23.5°S, 46.5°W), London (52.0°N, 0.0°) and New York (40.4°N, 74.0°W) as the destination. The average hop count and average propagation delay of IMHCR and MHCR are shown in Figure 23. The results show that IMHCR can always reduce the average hop count, but its effect is not significant between cities with similar latitudes, such as from Beijing to London and New York; and from Beijing to Cape Town and Sydney, where the latitude difference is large, the average hop count is decreased significantly by IMHCR; and from Beijing to Sao Paulo, although the latitude difference is large, the average hop count does not decrease significantly. When the hop count of IMHCR and MHCR are similar, the average propagation delays of them are also close; only when the



(a) Average Hop Count comparison (b) Average Propagation Delay comparison

Figure 23: Comparison of end-to-end hop count and propagation delay

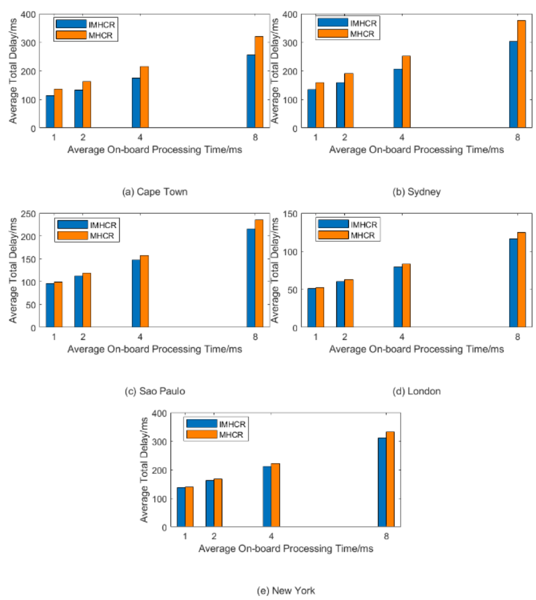


Figure 24: Comparison of end-to-end total-delay

IMHCR can significantly decrease the average hop count, can the average propagation delay be significantly reduced.

After taking on-board processing time into account, which takes 1, 2, 4 and 8ms as value, the end-to-end average total delay of IMHCR and MHCR are shown in Figure 24. It can be seen that as the average on-board processing time increases, the performance improvement of IMHCR will gradually increase compared to MHCR.

In summary, compared with MHCR, IMHCR can always reduce the average hop count and average total delay, but its effect is closely related to the relative geographical positions between ground terminals.

5 CONCLUSION

In this paper, we proposed an improved minimum hop count routing (IMHCR) algorithm based on the optimal network topology in LEO Mega-Constellations. The simulation results show that compared with the minimum hop count routing (MHCR) algorithm, IMHCR can significantly reduce the hop count, propagation delay and total delay overall; in terms of ground end-to-end routing, the improvement effect of IMHCR is affected by relative geographical positions between ground terminals.

In future work, we look forward to studying the impact of the relative geographical positions between ground terminals on the hop count and delay in the IMHCR algorithm, as well as the impact of the phase factor F of LEO Mega-Constellations on the algorithm.

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