Handover Scheme of LEO Satellite Network Based on Geographical Division Scenario

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Abstract. On the basis of completing the division of geographical regions, for the problem of satellite mobile handover, this paper proposes a satellite selection algorithm for selecting the satellite with the longest coverage time to reduce the handover rate. Also based on the idea of "centralized location management", this paper proposes the satellite handover scheme based on the geographical division scenario to update the satellite routing table entries and ensure the correct routing of data packets. Regarding the user handover problem, based on the idea of "decoupling data transmission and address update", a user handover scheme based on geographical division scenario is proposed, which reduces handover delay and signaling overhead compared to traditional satellite network handover schemes.

1. Introduction
With the development of space technology, the need for real-time and reliable communication between mobile hosts and ground users has become more obvious. The future trend of designing global communication systems is to combine satellite communications with terrestrial communications. Mobile handover is a key technology of mobile satellite communication networks. When a mobile host hands over between different access points, a mobile handover scheme is required to maintain the continuity of data transmission between the two parties.

LEO satellites revolve around the earth and hand over between ground stations when passing through different areas on the earth's surface; spacecraft or ground mobile nodes communicate with other ground nodes through relay satellites, and the satellites act as routers to forward data. However, in this scenario, the satellite moving speed is high, and users within the satellite coverage area need to hand over every few minutes on average [1]; and the satellite needs to maintain a routing table entry for each user, resulting in the satellite's on-board routing table too long, and the routing table needs to be updated every time the user changes the IP address, so it is difficult to establish an address aggregation relationship between the satellite and the ground user terminal.

In the geographical division scenario, the satellite and geographical area "one-to-one" access not only maintains the address convergence relationship, but also reduces the number of on-board routing table entries, speeds up routing convergence, and avoids ground users' frequent and passive handover caused by high satellite moving speeds. We stipulate that when the midpoint of the division is within the coverage of the satellite, the access is successful; once the midpoint of the division leaves the coverage of the dominant satellite, handover will occur.
In this paper, we do not pay attention to how the IP address is allocated during the handover process, nor do we pay attention to the specific routing mechanism. Related work has been implemented in [2] [3]. Based on the assumption that the geographical division has been completed, the specific handover process has been studied. Compared with the traditional satellite network scenario, there are two handover roles in the geographical division scenario, including satellite handover and user handover, as shown in figure 1. This paper focuses on the handover execution process, and proposes a corresponding handover scheme, which reduces the handover rate, reduces the time of user communication interruption, and realizes the correct routing of data packets. And through theoretical analysis and simulation, explains the advantages of the proposed algorithm or scheme, and provides certain ideas and references for the handover problem of low-orbit satellite networks.

2. Related work

2.1. Satellite selection algorithm
When the satellite hands over between different geographic regions, there are 2 to 3 satellites available for the current region. The greater the latitude, the more candidate satellites. [4] proposed a satellite-to-ground link handover algorithm, which selects the shortest distance satellite. Although this method is simple to implement, there is no guarantee that the satellite will still be able to cover this subarea at the next moment, resulting in a higher handover rate. [5] proposed a satellite selection algorithm based on signal strength. This method needs to calculate the neighbor cell list of the terminal, and needs to update the handover weights at all times. There is a certain algorithm time-consuming, which will increase the handover delay.

In recent years, there have also been many methods that combine these satellite selection criteria with graph theory [6], fuzzy neural networks, etc., but these methods have two main problems. One is that the design of input parameters is very complicated. For example, in [7], one of the input parameters is the reference signal received power (RSRP). Although this parameter is a key parameter in the terrestrial LTE network, it is difficult to measure this parameter in real time in the actual satellite network. Secondly, these methods require a large amount of training data sets, and we lack data support and environmental support for these algorithms.

2.2. Handover scheme
As for the satellite handover process, there is currently no relevant research work. For the handover of ground mobile terminals, it is mainly divided into hard handover based on mobile IP and soft handover based on SCTP protocol [8]. The handover delay of the mobile IP handover scheme is relatively large;
and if the satellite uses soft handover when hands over between different geographic regions, the satellite needs to have two data antennas, and the midpoint of the geographic region must be in the overlapping area covered by the old and new satellites. In actual scenario, the new access handover process will be initiated when the old satellite no longer covers the geographic area; if the user terminal adopts soft handover when hands over between different geographic areas, the user terminal needs to be in the overlapped area of the geographic area. However, there is no overlapping area of coverage between geographic regions, which is inconsistent with the actual scenario. Therefore, only hard handover can be used for both satellite handover and user handover.

3. Scheme design

3.1. Satellite selection algorithm

In view of the geographic division scenario as described above, handover occurs when the satellite no longer covers the midpoint of the geographic region. How to choose the dominant satellite in the current region can make the coverage time the longest and the handover rate the lowest. To solve this problem, a prediction model of coverage time based on satellite ephemeris is proposed in this section.

Figure 2 shows the relative geometric relationship between the satellite and the earth, S represents the position of the satellite, U represents the location of the user terminal, H represents the location of the sub-satellite point, \( R_e \) represents the radius of the earth, h represents the height of the satellite, and t represents the elapsed time after the terminal enters the satellite coverage, \( \theta(t) \) is the current elevation angle. When the terminal is at the boundary of the satellite coverage area, it has the minimum elevation angle \( \theta_{\text{min}} \). In the Earth-centered Earth-Fixed Coordinate System (ECEF), the angular velocity of low-orbit satellites changes very little (less than 3\%) in most circular orbits [9], so we assume that the satellite's angular velocity \( \omega \) in the Earth-centered Earth-fixed coordinate system is a fixed value, at this time the trajectory of the sub-satellite point is a large arc.

![Figure 2. The relative geometric relationship between the satellite and the earth.](image)

The satellite has a fixed trajectory, so we can use the effective information of the satellite ephemeris to realize the satellite selection algorithm. From [10], the real-time elevation angle prediction model of the satellite can be obtained, as shown in the formula (1).
\[ \theta(t) = \tan^{-1}\left\{ \frac{\cos((\omega_e \cos \gamma_m^0) \cos \gamma_m) \times \cos \gamma_m - \frac{R_e}{R} \cos \theta_{\min}}{\sin(\cos^{-1}((\omega_e \cos \gamma_m^0) \cos \gamma_m) \times \cos \gamma_m - \frac{R_e}{R} \cos \theta_{\min})} \right\} \]  

(1)

\[ R = R_e + h \]  

(2)

\( \omega_s \) is the angular velocity of the satellite in the Earth's Inertial Coordinate System (ECI), which is a fixed value, \( \omega_e \) is the angular velocity of the earth's rotation, \( i \) is the orbital inclination of the satellite constellation, and \( \gamma_m \) is the trace angle, which represents the minimum angular distance between the sub-satellite point position of the satellite and the user terminal.

When handover occurs, first calculate the elevation angle of the midpoint of the current zone relative to each satellite, and then substitute the current elevation angle according to the real-time elevation angle prediction model proposed in [10] to obtain two times \( t_{p1} \) and \( t_{p2} \). According to the timestamp in the broadcast message, judge whether the satellite is far away or close to the partition. By choosing between the two times, the elapsed time \( t_p \) from the minimum elevation angle to the handover time can be obtained.

In a low-orbit satellite constellation, the satellite coverage time is exactly twice the elapsed time for the satellite elevation angle to change from \( \theta_{\min} \) to \( \theta_{\max} \), so the total satellite coverage time \( t_{cov} \) is shown in equation (3):

\[ t_{cov} = 2 \frac{\cos^{-1}(\cos \gamma_0)}{\omega_s - \omega_e \cos \gamma_m} \]  

(3)

and

\[ \gamma_0 = \cos^{-1}\left( \frac{R_e}{R} \cos \theta_{\min} \right) - \theta_{\min} \]  

(4)

Finally, the difference between the two times \( t_{cov} \) and \( t_p \) can be used to obtain the remaining coverage time of each satellite, and finally the satellite with the longest coverage time is selected among all the candidate satellites.

3.2. Handover scheme

Compared with the traditional satellite network scenario, the handover in the geographical division scenario is a dual handover, including the handover of satellites between different geographical divisions and the handover of users between different geographical divisions.

The topology of the satellite network has been changing dynamically. The handover of satellites between different geographical regions will cause the change of the satellite IP address. If the OSPF dynamic routing protocol is adopted, these two factors will cause frequent updates of the satellite routing tables. So when the route has not yet converged, it will cause the wrong route of the data packet, resulting in a lot of packet loss. Because the satellite has a constant motion pattern, we can use static routing to transmit data packets. During initialization, the routing table is generated at each time according to the changes in the satellite network topology. When each satellite transmits data packets, it only needs to find the next hop according to the destination address on the routing table at the current time, and the route convergence time is 0.

However, the static routing algorithm only solves the problem of changes in the satellite network topology. When the geographic area changes the dominant satellite, that is, when the IP address of the satellite changes, the corresponding IP address in the routing table entry needs to be updated in time to send the data packet to the correct destination. The specific satellite network topology is shown in figure 3, and the connection relationship between the nodes is given. We have introduced a ground control center to achieve centralized location management. We use high-speed laser links between satellites,
and use low-speed links between satellites and ground stations, and all ground stations are connected with the control center and connected with the corresponding satellites.

Figure 3. Satellite network topology.

During initialization, the data packet routing table at different times is generated according to the topological connection of the satellite network at each time, and this table is updated regularly for data packet transmission. When the midpoint of the geographic area is not within the coverage of the current dominant satellite, the satellite with the longest coverage time is selected according to the satellite selection algorithm, and then the specific handover process is performed. During the handover, the satellite will send the updated geographic region and IP address of the dominant satellite mapping relationship to the ground control center, and then the ground control center will directly broadcast the changed geographic region and IP address of the dominant satellite mapping relationship to each satellite. After each satellite receives it, it will change the IP address of the corresponding satellite in the routing table entry, indicating that the routing path of the data packet to this satellite has not changed, but the IP address has changed. The signaling interaction sequence diagram of the entire satellite handover process is shown in figure 4.

Another type of handover in the geographical division scenario is user handover. Since there is no overlapping coverage area in the geographical area, user handover in the geographical division scenario can only be a hard handover. The reason why the hard handover based on mobile IP has a large handover delay and low efficiency is because it has a restriction that a local agent entity must be set for each network segment, and in the handover process, the local agent can forward the data packet from the communication node after completing the registration process.
In the user handover solution proposed in this paper, we can decouple the data transmission process and the address update process, adopt centralized location management, set up a ground control center, and lift the restriction of one local agent for each network segment. When the user hands over, the newly-accessed satellite sends the address mapping relationship to the ground control center for maintenance, and at the same time informs the correspondent node to route the data packet directly to the new address. So the data transmission process and the address update process are implemented in parallel. This not only reduces the handover delay, but also improves the transmission efficiency of data packets. The signaling interaction sequence diagram of the entire handover process is shown in figure 5.

![Figure 4. Signaling interaction sequence diagram of satellite handover process.](image)

![Figure 5. Signaling interaction sequence diagram of user handover process.](image)
4. Simulation analysis and discussion

4.1. Simulation scenario
The simulation software uses STK to build an Iridium constellation. Each orbital surface is circular, the orbital inclination and the orbital radius are fixed, the orbital height is 780km, and the minimum elevation angle is 8.2°. This paper adopts a uniform zoning scheme, that is, a geographical division scheme in which a circle inscribes a trapezoid. Based on the simulation results of this division scheme, it can be concluded that when handover occurs in the middle and low latitudes, there are 2~3 candidate satellites available for the current division (all are idle satellites, without access to any geographical division). The greater the latitude, the more candidate satellites.

The simulation duration of the scenario is set to 24 hours, which is 86400s, and the static routing table is generated with a time step of 1s, the topology update cycle is also 1s, the link delay is set to 3ms, and the processing delay of each signaling is set to 3ms. The inter-satellite link bandwidth is set to 1Gbps, and the satellite-to-ground link bandwidth is set to 100Mbps. We only consider the one-way data transmission process from the communication node to the user in the geographical division. The communication node uses the Poisson process to generate data flow. The number of data packets generated by the communication node per unit time is a random variable and obeys the Poisson distribution. The average value is $\lambda$, the value of $\lambda$ is set to 100, and the time interval for sending data packets is 1ms.

4.2. Satellite selection algorithm
The sampling interval of sub-satellite data samples in the satellite coverage area selected in the simulation process is 1s. For the Iridium constellation, there are 675 sampling points. The accuracy of the elevation prediction model has been verified in [10]. In this paper, we have selected multiple coverage handover scenarios in the same geographical division at different times, and compared the coverage duration of the proposed satellite selection algorithm and the nearest satellite selection method at each handover time. The result obtained is shown in figure 6.

According to the result of figure 6, we can see that the coverage duration of the satellite selection algorithm proposed in this paper is significantly increased, which ensures that the dominant satellite selected during handover has the longest coverage time. At the same time, we also noticed that at some handover moments, the coverage durations obtained by the two satellite selection algorithms are the same, that is, the satellite with the longest coverage time is the nearest satellite, indicating that at this time, the midpoint of the division is near the sub-satellite track of the access satellite orbit.

![Figure 6. Comparison of coverage duration.](image)
We also found in the simulation process that when the nearest satellite is selected as the dominant satellite in one handover, the next handover will hand over to the last satellite with the longest coverage time, as shown in table 1. For example, at 3901 seconds, the access satellite (608) selected by the nearest satellite algorithm is actually the access satellite (608) selected by the satellite selection algorithm in this paper during the last handover. That is to say, the handover times of the satellite selection algorithm using the nearest satellite in the same time is twice the handover times of the satellite selection algorithm proposed in this paper. Therefore, the satellite selection algorithm proposed in this paper can greatly reduce the number of handovers and avoid frequent handovers.

Table 1. Access satellites selected by two satellite selection algorithms at different handover moments.

| Handover time/sec | 3604 | 4138 | 4668 | 5196 | 5720 | 6141 | 6697 | 7252 | 7806 |
|-------------------|------|------|------|------|------|------|------|------|------|
| The access satellite selected by the satellite selection algorithm in this paper | 608  | 607  | 606  | 605  | 102  | 102  | 101  | 111  | 110  |
| Handover time/sec | 3604 | 3901 | 4138 | 4464 | 4668 | 5025 | 5196 | 5584 | 5720 |
| The access satellite selected by the nearest satellite algorithm | 107  | 608  | 106  | 607  | 105  | 606  | 104  | 605  | 103  |

In summary, we can conclude that the closest satellite is often not the best choice when handover is performed in a geographical division scenario. The coverage time prediction model based on the satellite ephemeris proposed in this paper has high accuracy, can obtain the satellite with the longest coverage time, and reduces the handover rate.

4.3. Handover scheme

For the handover of satellites between different geographical division, first assign IP addresses to the satellite-to-ground ports according to the different network segments where the geographical division is located, then set the link connection relationship, and realize the interconnection and intercommunication between the various protocol models. When handover occurs, the geographical division first selects the next satellite to access according to the result of the satellite selection algorithm, and then executes the satellite handover process to update the address, ensuring the correctness of the data packet routing.

For the user handover between different geographical division, the data transmission process of users in the geographical division and communication nodes is first simulated. Then three different handover schemes, namely MIPv4, MIPv6, and user handover scheme based on geographical division scenario, are used for simulation verification.

We compared the signaling overhead and handover delay of the three handover schemes, as shown in figure 7. The handover scheme proposed in this paper reduces the signaling overhead of the MIPv6 handover scheme by 60%; the handover delay is 59% lower than the handover delay of the two traditional satellite network handover schemes.

In the MIPv4 handover scheme, the original satellite will forward the data packets sent by the communication node to the newly-accessed satellite through the inter-satellite link, which is relatively inefficient in routing, that is, "triangular routing." When the MIPv6 handover scheme performs handover, data packets must be received through the "triangular routing" process of the previous satellite. But when the user terminal receives the data packet forwarded by the previously connected satellite, it will realize that the correspondent node does not know the current new IP address of its own, so it will initiate the registration process to the correspondent node. Therefore, although the MIPv6 handover solution solves the "triangular routing" problem of subsequent data packet transmission, the signaling overhead during the handover process is relatively large. The user handover scheme we proposed does not need
to register with the previously accessed satellite, but requests the current access satellite to notify the communication peer node of the new IP address, so it will get lower handover delay and smaller signaling overhead.

Then we compared the throughput changes of the three handover schemes, as shown in figure 8. We can see that when no handover occurs, the ground user terminal can normally receive the data packet from the communication node. After the start of the handover process, the throughput of the three schemes will drop to 0, because the three schemes are based on hard handover. However, we can see that the user handover scheme proposed in this paper has the shortest throughput time of 0. The reason why the throughput of the MIPv6 handover scheme will increase after the handover is completed instead of returning to the original normal level is that the MIPv6 scheme solves the "triangular routing" problem through the registration process with the CN and speeds up the subsequent data packet transmission. Superimposed with data packets that have not been sent before, resulting in a temporary increase in throughput.

![Figure 7. Comparison of signaling overhead and handover delay of handover schemes.](image-url)
To sum up, the satellite handover scheme based on geographical division scenario proposed in this paper realizes the dynamic update of addresses and solves the problem of incorrect routing of data packets. The user handover scheme based on geographical division scenario achieves the least number of interactions, the least handover delay, and the least packet loss on the basis of hard handoff, thereby ensuring the continuity of communication and the quality of service.

5. Conclusion
In the geographical division scenario, for the satellite mobile handover problem, this paper proposes a satellite selection algorithm based on the geographical division scenario, selects the satellite with the longest coverage time, and reduces the handover rate. And based on the idea of "centralized location management”, proposes a satellite handover scheme based on geographical division scenario, updating the satellite routing table entries to ensure the correct routing of data packets. For user handover issues, based on the idea of "decoupling data transmission and address update", a user handover scheme based on geographical division scenario is proposed. Compared with the traditional satellite network handover schemes, it reduces signaling overhead and handover delay. The above-mentioned scheme is simulated and verified in the Iridium constellation scenario. The simulation results show the advantages of the scheme proposed in this paper, which can better guarantee the continuity of communication and the quality of service.

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