LISP-LEO: Location/Identity Separation-based Mobility Management for LEO Satellite Networks

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***Abstract*—In space-terrestrial integrated networks, the relative motion between LEO satellites and ground terminals is inevitable, which will trigger the reassignment of the terminal IP addresses and disrupt the ongoing TCP connections. Traditional Mobile IP protocol can solve the problem by using the home agent and the tunneling mechanism. However, for space-terrestrial integrated networks, Mobile IP is inefficient as it introduces (1) increased latency when registering with the remote home agent, (2) high packet loss due to large registration latency, (3) triangular routing to the remote home agent. To address the above issues, we propose LISP-LEO, a location/identity separation-based mobility management protocol for LEO satellite networks. Specifically, (1) we divide the Earth's surface into partitions and maintain a partition-satellite mapping table in real-time according to the regularity of satellite motion, (2) we always route traffic to the satellite above the destined terminal by querying the partition-satellite mapping table, which eliminates triangular routing and the related performance overheads, (3) we handle the corner case that multiple satellites occur above the destined terminal by proposing last-hop relay. The evaluation convinces that, for the LEO-48 constellation, LISP-LEO produces a 55.0% reduction in the RTT and a 45.8% reduction in the number of forwarding hops in the worst routing case compared with Mobile IP.**

I. Introduction

Due to the broader Earth's surface coverage as well as very few terrain restrictions, satellite networks are considered as a good complement to terrestrial networks and have regained a lot of attention from both academia and industry. Compared with MEO and GEO satellites, LEO satellites are smaller in size, less expensive, closer to the ground, yielding much lower space-ground transmission latency. Furthermore, LEO satellite constellations have high-density mesh topologies, providing multi-path routing capabilities for traffic load balancing and link failure tolerance even in extreme cases. Considering the commercial value of the low latency and high reliability, as well as the declining satellite launch costs, several companies start to design and launch their mega-scale LEO satellite constellations into space, *e.g.*, SpaceX has proposed the Starlink project, planning to launch 12,000 LEO satellites and conduct inter-satellite routing for global Internet coverage [1].

One of the key challenges for the LEO satellite network is *mobility management*. For a typical LEO satellite constellation, the orbital altitude is less than 2000km, making the Earth's coverage area of a single satellite small. Moreover, the relative motion between LEO satellites and ground terminals occurs frequently, making the duration of GSLs (Ground-to-Satellite Links) short. During the terminal-to-terminal communication via the LEO satellite network, terminal-satellite handovers are inevitable. However, at the network layer, such a handover will cause the reassignment of the terminal IP address and thereby disrupt the running TCP connections because a TCP connection is established with a fixed pair of 5-tuple socket addresses. The disrupted TCP connections will further affect the carried services as well as the end-user experiences.

Most of the prior work focuses on the link-layer handover to address the transfer of an ongoing link connection to a new spot beam or satellite [2], [3], while studies on network-layer mobility management are quite few. For the latter, some existing solutions borrow the ideas of mobility management protocols from terrestrial networks and apply them to LEO satellite networks [4], [5]. Taking Mobile IP [6] as an example, it proposes two different IP addresses to identify a mobile terminal and its location. One is the HoA (Home Address), which indicates a unique name of the mobile terminal and is not subject to change; the other is the CoA (Care-of Address), which specifies the location of the mobile terminal in the network. A home agent of a mobile terminal is the satellite above the mobile terminal in the initial stage. Upon a satellite handover, the mobile terminal obtains a new CoA from the new satellite (*i.e.*, the foreign agent) and sends a binding update to the home agent. With the binding update operation, we can associate the HoA with the CoA at the home agent to keep communication continuous after handover. The home agent sends the packets destined for the mobile terminal through a tunnel to the CoA. After arriving at the end of the tunnel, each packet is then delivered to the mobile terminal.

However, due to satellite motion, the distance between the home agent and the mobile terminal varies constantly. Sometimes, the time for registration with the home agent can be very long. The high registration latency will cause severe packet loss because the packets destined for the terminal's original CoA will be lost during the registration. Moreover, Mobile IP has the so-called triangular routing problem [7]. When a source terminal sends traffic to the mobile terminal, packets will first reach the home agent. Then, the home agent

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encapsulates these packets and tunnels them to the foreign agent. Finally, the foreign agent decapsulates these packets and delivers them to the mobile terminal. The packet route is triangular and inefficient. In the worst case, when the mobile terminal is close to the source terminal while its home agent is on the other side of the Earth, the packets destined for the mobile terminal have to traverse the Earth twice.

To overcome Mobile IP's limitations, we propose LISP-LEO, a novel location/identity separation-based network-layer mobility management protocol dedicated to LEO satellite networks. In our design, we divide the Earth's surface into multiple partitions and establish a partition-satellite mapping table. The mapping relationship is dynamic since the satellite above a partition changes persistently (here we call the satellite above a partition the service satellite). Then, we propose a new IP addressing method based on location/identity separation. The terminal's new address contains two parts: PID (Partition Identifier) and IID (Identity Identifier). The former represents the partition where the terminal is located; the latter indicates its identity. Under this definition, the terminal's address will not be changed when a satellite handover occurs. To avoid triangular routing, we always route traffic to the satellite above the partition where the destined terminal is located (*i.e.*, its service satellite) by querying the partition-satellite mapping table using the PID part of the destination IP address. Then, we encapsulate the original packets using the source and destination satellite identifiers and tunnel them to the service satellite. Sometimes, there are multiple satellites above the destined terminal, that is, the terminal's service satellite may be different from its access satellite. When these packets reach the service satellite, the service satellite will directly deliver them to the terminal, or it will perform additional one-hop relay to deliver them to the access satellite, from which these packets will finally be delivered to the terminal. In LISP-LEO, the service satellite is similar with the home agent in Mobile IP. The only difference is that the service satellite is always near the mobile terminal while the home agent may be far away from the terminal which yields triangular routing.

Our major contributions are summarized as follows:

- We propose a novel IP addressing method based on location/identity separation, using different fields of the address to separately identify the terminal's location and identity. Since the location information of the new address represents the partition where the terminal is located, the terminal's address need not be changed when a satellite handover happens.
- We divide the Earth's surface into partitions and maintain a partition-satellite mapping table according to the regularity of satellite motion. We always route traffic to the satellite above the destined terminal by querying the mapping table, resolving triangular routing in Mobile IP.
- We deal with the corner case where the satellite above the destined partition is not the access satellite of the destined terminal via last-hop relay for accurate traffic delivery.
- The evaluation convinces that, for the LEO-48 constellation, LISP-LEO produces a 55.0% reduction in the RTT and a 45.8% reduction in the number of forwarding hops in the worst routing case compared with Mobile IP. Moreover, LISP-LEO also reduces packet loss during satellite handover to a great extent.

II. Location/Identity Separation-based Protocol

LISP-LEO is a sophisticated mobility management protocol and we discuss its technical details step by step. First, we divide the Earth's surface into partitions. Then, we establish a one-to-one mapping between partitions and satellites. After that, we design a location/identity separation-based addressing method for each mobile terminal on the ground to keep its IP address unchanged during satellite handover. To let the terminal be aware of its access satellite, each satellite will broadcast to the ground. On receiving the broadcast signals and updating its access satellite, the terminal will register with its service satellite. Finally, we discuss the end-to-end packet transmission process between two mobile terminals, covering techniques such as tunneling and last-hop relay.

A. Partition Design

A typical $M \times N$ LEO satellite constellation consists of M orbital planes and each orbital plane accommodates N satellites. All satellites in the constellation work together to cover the complete Earth's surface. Since the coverage area of a single satellite is circular, the coverage areas of two adjacent satellites may overlap. In this way, a mobile terminal can possibly be under the coverage of one or more satellites.

According to the number of satellites in the LEO satellite constellation and the coverage area of a single satellite, we divide the Earth's surface into multiple partitions. For simplicity, we consider a uniform division by latitude and longitude, resulting in the same number of partitions as the number of satellites. And the size of a partition is slightly smaller than the coverage area of a satellite. For a typical $M \times N$ constellation, we can obtain $M \times N$ partitions after division. Each of them spans $360°/N$ of latitude and $360°/(2 \times M)$ of longitude.

In our design, we assign each partition a unique PID for identification. Taking a 6×8 constellation as an example, we divide the Earth's surface into 48 partitions and the PIDs assigned to the partitions are from 1 to 48. Moreover, based on the latitude and longitude range of a partition, we can easily find the center of the partition. To implement our protocol, all satellites and mobile terminals on the ground need to store information about each partition, including its PID and center.

B. Partition-Satellite Mapping Table

Similar to partitions, we assign each satellite a unique SID (Satellite Identifier) as its identity, as shown in Fig. 1. Then we establish a one-to-one mapping between partitions and satellites. Each partition corresponds to the satellite with the maximum elevation angle from its center location. In our protocol, each satellite maintains a partition-satellite mapping table to store the mapping relationship. Each entry in the mapping table consists of a PID as the key and a SID as the value. For example, in Fig. 1, the partition n corresponds to the satellite S_j, which is recorded in an entry $\{n,\ S_j\}$ in the partition-satellite mapping table.

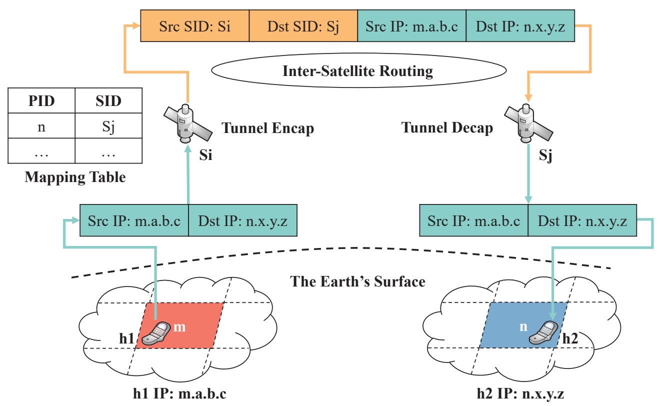

Fig. 1. In LISP-LEO, the packets sent from the source terminal (h1) to the destination terminal (h2) will first query the partition-satellite mapping table in the satellite above the head (S_i), using the PID (n) in the DIP to obtain the corresponding SID (S_j), then encapsulated and tunneled via inter-satellite routing to the satellite (S_j) above the destination terminal (h2).

As satellites periodically fly over the Earth's surface, the mapping relationship keeps changing. Therefore, each satellite needs to update its mapping table according to the regularity of satellite motion. The update process is as follows:

- First, each satellite obtains its location (*i.e.*, its latitude and longitude information) via GPS. According to the real-time satellite location prediction approach [8], the satellite estimates the location of other satellites thanks to the regularity of the LEO satellite constellation.
- Second, for each satellite, the elevation angle between the center of each partition and each satellite will be calculated one by one, according to the pre-stored partition information and the location information of each satellite obtained in the previous step.
- Finally, for each satellite, all the entries of the partition-satellite mapping table will be updated. Specifically, in the mapping table, each partition will be associated with the satellite which has the maximum elevation angle from the center of that partition (*i.e.*, the nearest satellite).

C. Location/Identity Separation-based Addressing

Based on the above partition design, we introduce a new addressing method based on location/identity separation. The terminal's address is designed to consist of a PID and an IID:

$$\text{IP Address} = \text{PID} + \text{IID}.$$

In the new address, the PID indicates the terminal's location and represents the partition where the terminal is located; the IID is used to identify the terminal. As shown in Fig. 1, the terminal h1 is located in the partition m and its address is $m.a.b.c$. Here, we follow the rule of the Class A IPv4 address. The first 8 bits of the address are used for the PID and the remaining 24 bits represent the IID. Moreover, to avoid conflicting with others' IIDs when a mobile terminal moves into a neighbor partition, its IID should be globally unique.

Each mobile terminal obtains its address by calculating its PID and IID. The calculation rules are as follows:

- PID: The mobile terminal obtains its location via GPS and calculates the partition containing the location according to the pre-stored partition information.
- IID: The mobile terminal has been assigned a constant IID in advance which will not be changed.

According to the proposed addressing method, when a mobile terminal moves within a partition, its address will remain unchanged even if a satellite handover occurs.

D. Satellite Broadcast

As described earlier, each mobile terminal on the ground is covered by at least one satellite to meet its communication requirements. When a mobile terminal moves into the overlapping coverage areas of multiple satellites, it is necessary to select the most suitable access satellite as its current point of attachment to the LEO satellite network. To achieve this, we design a satellite broadcast mechanism. Each satellite periodically broadcasts within its coverage area to advertise its service. Each broadcast message contains information about the corresponding satellite, such as its SID and location.

The mobile terminal selects the most suitable access satellite relying on the broadcasts it receives. To have the best signal transmission quality, the mobile terminal will select the satellite with the maximum elevation angle (*i.e.*, the nearest) as its access satellite [3]. Specifically, after receiving the broadcasts from multiple satellites, the terminal will obtain the location of these satellites from the broadcasts. The satellite location will be used together with the terminal's location obtained from GPS to calculate the satellite with the maximum elevation angle, which will be selected as the terminal's access satellite.

E. Terminal Registration with the Service Satellite

According to the mapping relationship described in §II-B, the satellite associated with a partition is defined as the service satellite of the mobile terminals in that partition. In our protocol, the service satellite is considered to play an important role similar to the home agent in mobile IP. Therefore, we also need a similar registration mechanism to record the mobility bindings at the service satellite. Specifically, after updating its access satellite, each mobile terminal must register with its service satellite. Such registration creates or modifies a mobility binding at the service satellite to associate the terminal's address with its access satellite's SID.

As mentioned earlier, the coverage area of a satellite is slightly larger than the size of a partition. Moreover, according to the maximum elevation angle rule, a terminal's access satellite is closest to itself. As a comparison, a terminal's service satellite is closest to the center of the partition where the terminal is located. Therefore, a terminal's service satellite is either the access satellite or one of the four adjacent satellites of the access satellite. To deal with the two cases, our protocol defines two different registration procedures, one registering directly with the terminal's service satellite, and the other registering via a non-service satellite that relays the registration to the terminal's service satellite one-hop away. The following rules specify the different conditions to use the above two registration procedures:

- Direct: If a mobile terminal's access satellite happens to be its service satellite, the mobile terminal must register directly with its service satellite.
- Indirect: If a mobile terminal's access satellite is not its service satellite, the mobile terminal must register indirectly with its service satellite via its access satellite.

Both registration procedures involve the exchange of the Registration Request and Registration Reply messages. As shown in Fig. 2, when registering directly with the service satellite, the registration procedure only requires the following two messages:

1) The mobile terminal sends a Registration Request to the service satellite.
2) The service satellite responses a Registration Reply to the mobile terminal, granting the Request.

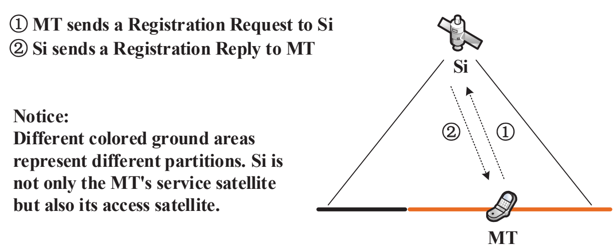

Fig. 2. Registering directly with the service satellite.

As shown in Fig. 3, when the terminal registers indirectly with the service satellite via the access satellite instead, the registration procedure requires the following four messages:

1) The mobile terminal sends a Registration Request to the access satellite to start the registration process.
2) The access satellite processes the Registration Request and then relays it to the service satellite one-hop away.
3) The service satellite sends a Registration Reply back to the access satellite to grant the Request.
4) The access satellite processes the Registration Reply and then relays it to the mobile terminal to inform it of the disposition result of its Request.

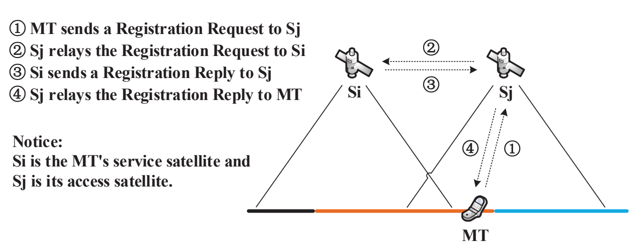

Fig. 3. Registering indirectly with the service satellite.

To avoid registration failure due to packet loss or other issues, each time a mobile terminal sends a Registration Request, it will start a timer with a reasonable waiting time. If no Registration Reply has been received within the waiting time, it will resend a new Registration Request. The setting of the timer needs to consider the RTT of space-terrestrial communication as well as the latency to process the messages.

In the proposed registration mechanism, when a satellite handover occurs, each mobile terminal will register with its service satellite. As satellites periodically fly over the Earth's surface, a terminal's service satellite and access satellite keep changing all the time. However, since a terminal's service satellite is either the access satellite which is always closest to itself, or one of the four adjacent satellites of the access satellite, the distance between the service satellite and the mobile terminal does not increase too much during satellite motion and remains in a stable range. Proportional to the distance between the terminal and the service satellite, the registration latency is also bounded within a stable range.

Note that the satellite broadcast interval has an impact on the timeliness of registration when a satellite handover occurs. If the interval is too large, the terminal may not receive the broadcasts to update its access satellite in time even after handover, which will delay the registration with the service satellite. This will cause potential packet loss because the traffic may be routed to a new service satellite but the new service satellite has no idea about how to route the traffic to the terminal or its access satellite without the latest registration information. On the contrary, if these broadcasts can be triggered frequently (*e.g.*, every 1ms), the terminal will be sensitive to the satellite handover and complete registration immediately, at the cost of some message processing overhead.

F. End-to-End Transmission between Terminals

As mentioned in §II-B and §II-C, each satellite maintains a partition-satellite mapping table, containing a real-time mapping between each partition and the satellite closest to its center. Meanwhile, the PID in a terminal's address represents the partition where the terminal is located. Therefore, for communication between a ST (Source Terminal) and a DT (Destination Terminal), when a packet reaches the ST's access satellite, we can directly find the DT's service satellite by querying the mapping table using the PID of the destination address. After that, we can use the tunnel technique for packet routing between the ST's access satellite and the DT's service satellite. Specifically, the ST's access satellite is responsible for encapsulating the original IP packets and tunnelling them to the DT's service satellite. On the other end, the DT's service satellite is responsible for delivering these packets to the DT.

Underneath the tunnel, each satellite acts as a router with a routing table and forwards the packets. The routing table maintained by the satellite stores all the routes to other satellites. Essentially, the inter-satellite network is the underlay network of the overlay tunnel between the ST and the DT. And we use the SID of the ST's access satellite and the SID of the DT's service satellite as the source and destination addresses of the underlay route for tunneling the original IP packets. In this way, the inter-satellite network can be entirely independent from the ground network and we can use any inter-satellite routing protocol, such as OPSPF [8], to calculate the satellite routing tables. During inter-satellite routing, on receiving an incoming packet, the satellite will look up its routing table based on the destination SID in the outer packet header, determine the next hop and forward the packet.

Based on the above discussion, we describe the packet transmission process between terminals in detail:

1) The ST sends an IP packet to its access satellite to start the packet transmission procedure.
2) The ST's access satellite queries the local partition-satellite mapping table, encapsulates the packet, and then forwards it to the DT's service satellite.
3) The DT's service satellite queries the registration information (*i.e.*, the bindings between the terminals' addresses and the SIDs of their access satellites) and forwards the packet to the DT directly or indirectly.

There are two cases when the DT's service satellite forwards traffic to the DT. After receiving a packet, the service satellite queries the registered bindings to obtain the corresponding SID according to the DT's address in the inner packet header. Then, the service satellite compares the obtained SID with its SID, and there are two results. One is that the service satellite is the DT's access satellite, as shown in Fig. 1. In this case, the service satellite directly decapsulates the packet and forwards the packet to the DT through its interface towards the ground. The other result is that the DT's service satellite is not its access satellite. The handling of this case requires additional one-hop relay, as shown in Fig. 4. The service satellite needs to relay the packet to the access satellite first. To achieve this, the service satellite modifies the destination SID in the outer packet header to the obtained SID (*i.e.*, the access satellite's SID) and the source SID in the outer packet header to its SID. After receiving the packet, the DT's access satellite decapsulates and forwards the packet to the DT.

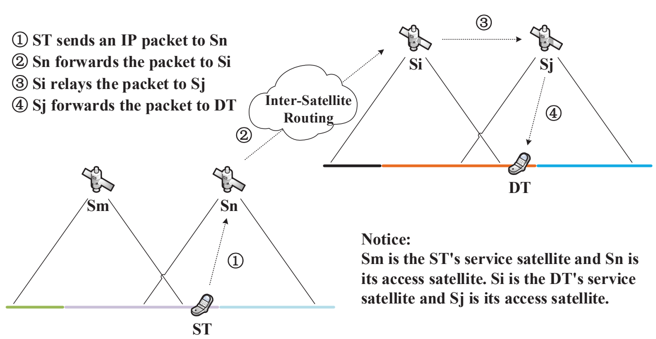

Fig. 4. Packet transmission between terminals (including last-hop relay).

To summarize, in LISP-LEO, the traffic from the ST is first forwarded to the DT's service satellite. If the DT's service satellite is not its access satellite, the service satellite needs to further deliver the traffic to the access satellite. As described above, if the DT's service satellite and access satellite are the same, there is no triangular routing. Otherwise, the route taken by the traffic destined for the DT can still be triangular. However, in this case, the terminal's service satellite and access satellite are only one-hop away from each other. So after arriving at the service satellite, the packets destined for the terminal only need additional one-hop relay to reach its access satellite. Consequently, in both cases, LISP-LEO can well address the triangular routing problem in Mobile IP.

III. EVALUATION

A. Methodology

To evaluate LISP-LEO, we build an LEO-48 satellite network testbed based on the Mininet network emulator. The parameter setting of the satellite constellation is listed in Table I. To emulate the LEO satellite network, we first configure the above parameter setting into STK 11.2 (a satellite constellation modeling tool) to generate the satellite trajectory for a period of time, which will be further fed into our testbed. We use Python to implement LISP-LEO. The emulation is performed on a desktop with an Intel Core i7-6700 quad-core processor and the Ubuntu 18.04 operating system.

TABLE I
PARAMETER SETTING OF THE LEO-48 SATELLITE CONSTELLATION

Major Parameters	Value
Number of Satellite Orbits	6
Number of Satellites in Each Orbit	8
Phase Factor	3
Satellite Altitude	780km
Time Period of Satellite Motion	6027s

B. Experimental Results

Fig. 5 shows the average registration time of two registration procedures. It indicates that indirect registration takes nearly twice as long as direct registration. When a mobile terminal registers indirectly with the service satellite, the registration request and the corresponding reply additionally go through the access satellite instead of being sent directly to the service satellite or the mobile terminal, which takes more time.

Fig. 6 shows the impact of the terminal location on the proportion of two different registration procedures. The three colors in Fig. 6 represent different distances between a mobile terminal and its partition center. As the mobile terminal gradually moves away from its partition center, the proportion of indirect registration increases from 0 to 0.5. This is because the closer the mobile terminal is to its partition center, the more likely that its access satellite and service satellite are the same satellite, making the proportion of indirect registration lower.

Fig. 7 shows the RTT of LISP-LEO and Mobile IP in one complete time period of satellite motion (around 6027s) between two fixed ground terminals. Besides, we also test the number of forwarding hops, and the result is shown in Fig. 8. In Mobile IP, the RTT and the number of forwarding hops fluctuate drastically during satellite motion, while they keep relatively stable in LISP-LEO. Compared with Mobile IP, LISP-LEO produces a 55.0% reduction in the RTT and a 45.8% reduction in the number of forwarding hops in the worst routing case. The above results prove that LISP-LEO is superior to Mobile IP and can well address triangular routing.

Fig. 9 shows the number of lost packets (due to satellite handover) of LISP-LEO and Mobile IP when the packet

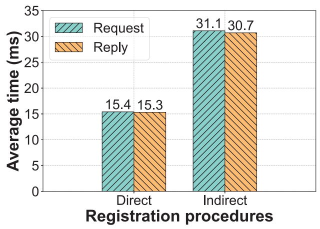

Fig. 5. The average time of two different registration procedures (*i.e.*, direct and indirect registration).

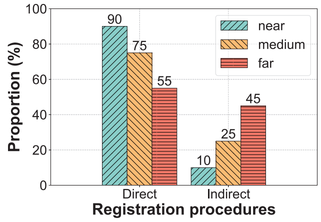

Fig. 6. The impact of the terminal location on the proportion of two different registration procedures.

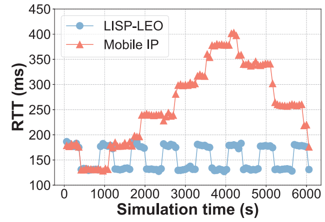

Fig. 7. The RTT of LISP-LEO and Mobile IP in one complete time period of satellite motion (6027s).

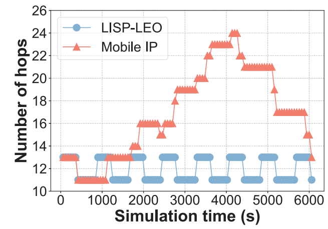

Fig. 8. The forwarding hop number of LISP-LEO and Mobile IP in one complete time period of satellite motion.

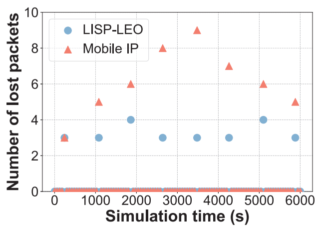

Fig. 9. The number of lost packets (due to satellite handover) of LISP-LEO and Mobile IP.

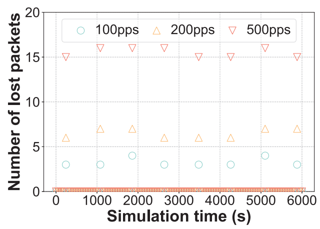

Fig. 10. The impact of packet transmission rate on the number of lost packets in LISP-LEO.

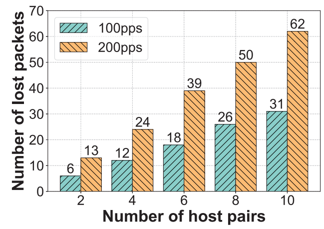

Fig. 11. The impact of the number of ground terminals on the number of lost packets in LISP-LEO.

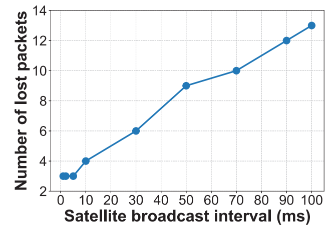

Fig. 12. The impact of the periodic satellite broadcast interval on the number of lost packets in LISP-LEO.

transmission rate of each ground terminal is set to 100pps. As shown in Fig. 9, packet loss occurs only when a satellite handover occurs. Compared with Mobile IP, LISP-LEO drops much fewer packets during satellite handover and has a 6% reduction in the number of lost packets in the worst case.

We also explore the impact of packet transmission rate on the number of lost packets (due to satellite handover) in LISP-LEO. Fig. 10 shows the number of lost packets at three packet transmission rates of 100pps, 200pps, and 500pps. The number of lost packets increases with the growth of packet transmission rate, and follows a linear relationship to the latter. Specifically, when the packet transmission rate is set to 200pps, the number of lost packets is about 7; for 500pps transmission rate, the number of lost packets is about 16.

Moreover, the number of lost packets (due to satellite handover) also increases with the growth of the number of ground terminals connected to one satellite as shown in Fig. 11. Here, we set the same number of fixed ground terminals in two partitions and the location of the terminals in the same partition is the same. Then, we let the terminals in different partitions communicate in pairs. When the packet transmission rate is set to 100pps, the number of lost packets for 6 pairs of terminals is 18, and that for 8 pairs of terminals is 26.

Fig. 12 investigates how the satellite broadcast interval impacts the timeliness of registration when a satellite handover occurs. The previous tests assume that the interval is small enough while the large interval will cause delayed registration, resulting in severe packet loss. When the interval is lower than 10ms, the number of lost packets for 100pps remains relatively stable due to the low packet transmission rate and the terminal's timely registration. However, when the interval is more than 10ms, the handover latency increases with the growth of the interval, as does the number of lost packets.

IV. Conclusion

In this work, to address the performance issues caused by triangular routing in Mobile IP for space-terrestrial integrated networks, we propose LISP-LEO, a location/identity separation-based mobility management protocol for LEO satellite networks. LISP-LEO maintains a dynamic partition-satellite mapping table in real-time and always routes traffic to the satellite above the destined terminal by querying the mapping table. This eliminates the remote home agent in Mobile IP and thereby resolves the inefficient triangular routing problem. The evaluation shows that, for the LEO-48 constellation, LISP-LEO produces a 55.0% reduction in the RTT and a 45.8% reduction in the number of forwarding hops in the worst routing case compared with Mobile IP.

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