A rerouting-controlled ISL handover protocol for LEO satellite networks

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Abstract

In this paper, a rerouting-controlled ISL (Inter-Satellite link) handover protocol for LEO satellite networks (RCIHP) is proposed. Through topological dynamics and periodic characterization of LEO satellite constellation, the protocol firstly derives the ISL related information such as the moments of ISL handovers and the intervals during which ISLs are closed and cannot be used to forward packet. The information, combined with satellite link load status, is then been utilized during packet forwarding process. The protocol makes a forwarding decision on a per packet basis and only routes packets to living and non-congested satellite links. Thus RCIHP avoids periodic rerouting that occurs in traditional routing protocols and makes it totally unnecessary. Simulation studies show that RCIHP has a good performance in terms of packet dropped possibility and end-to-end delay.

Keywords: LEO satellite networks; ISL handover; rerouting

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1. Introduction

In contrast to geostationary (GEO) satellites, communication system based on Low Earth Orbit (LEO) constellation has many advantages such as low propagation delay, lower power requirements in the user devices and efficient spectrum utilization. Owing to these intrinsic merits, LEO satellite networks with on-board processing and routing capabilities have attracted more and more attention from academic and industrial communities during recent years. It is expected that LEO satellites will become an integral part of the evolving next generation networks [1].

However, there are many issues to be addressed to make satellite networks service fully available to civilians. ISL (inter-satellite Link) handover is one of those challenges. Generally, LEO satellite is located at the altitude ranging from 500 to 1,500 km with a period of about 2 hours. Due to high mobility of satellite, ISLs which are used to forward packets will be shut down temporarily or periodically. For instance, in polar LEO satellite networks, ISLs must be turned off when satellites go into polar area [2]. As a consequence, ongoing communications using those ISLs have to be rerouted. This process is often referred to as ISL handover [3]. ISL handover is caused by the change of connectivity patterns of satellites and it happens when ISLs would be temporarily switched off due to the change in distance and viewing angle between satellites in neighbor planes. Then the ongoing connections using these ISL links have to be rerouted, causing ISL handovers [4]. Frequent handovers will cause a large amount of rerouting simultaneously.

As a result, network performance will be greatly impacted. First, Frequent handovers will cause a large amount of rerouting simultaneously, which incurs additional routing protocol overhead and degrades the overall performance of whole network. Because dynamic routing protocols update their routing tables through link dynamics notification, frequent rerouting will incur substantial routing overhead. Consequently, dynamic routing protocols which work quite well in wired network are not suitable for LEO satellite IP networks. Second, during the process of ISL handover packets will be dropped, which is caused by the non-convergent state of routing protocols. Last, the end-to-end delay will oscillate severely during ISL handover. With ISL links being switched off and turned on periodically, the number of IP hops between the two communication end terminals also changes accordingly. Because the propagation delay is the dominant factor of delay in satellite networks, the delay will change dynamically. Sometimes, the delay due to ISL handover will become excessively high and will make the service unacceptable under some quality of service (QoS) constraints.

In this paper, a rerouting-controlled ISL handover protocol (RCIHP) based on topology dynamics for LEO satellite network is proposed. The object of this protocol is to minimize rerouting attempts while to keep the end-to-end delays as low as possible. LEO satellite network presents a dynamic but periodic topology as characterized systematically in [5]. Because of the periodic topology dynamics, the moments in which ISL link will handover can be learned in advance and the prior knowledge can be used to control rerouting signaling resulting from ISL handovers.

The remaining of this paper is organized as follows. In section 2, some related work is described. In section 3, the protocol is presented in detail. In section 4, the performance is evaluated through simulation. Finally, we summarize the protocol in section 5.

2. Related work

Recently, many studies about the issues of handover management have been conducted [3], [4][6][7]. In [3], three kinds of handovers which consist of spotbeam handover, satellite handover, ISL handover are classified. The three types of handovers are all referred to as link handovers because they result from topological dynamics in LEO satellite networks and a specific link issue needs to be resolved in order to make the satellite network service complete. While spotbeam handover switches user traffic between spotbeams, satellite handover switches end user's connection between satellites. ISL handovers, as we mentioned before, which occurs when satellites enter into the polar area is our main research topic of this paper. Specially, we focus on ISL handover in polar LEO satellite networks.

While most researchers concentrate on spotbeam handover and satellite handover, seldom work is conducted to handle ISL handover management. There are only a few research articles about ISL handover. These algorithms either adopt the routing protocol which will incur the least handover events [8], or totally exclude all links that will be switched off during the process of communication [6]. Consequently, it can be unfair in the usage of the links [4]. Moreover, the link load status is not considered in these algorithms. In [6], a Probabilistic Routing Protocol (PRP) is introduced to handle ISL handover. The protocol removes all the ISLs that may experience a handover during the route establishment of voice call. Since there is no call holding time prior, the authors assume a probabilistic distribution function (PDF) for the call duration time. During the call time, all ISLs that may experience handover will be excluded from the routing table. The new call blocking probability will be excessively high under some conditions and leads to possible under-utilization of some links. For instance, if a call duration time is 10 minutes; an ISL link will be excluded from the forwarding path for 10 minutes. However, the ISL link might be in a closed state only for a short period (say, 1 minute).

3. Rerouting-Controlled Isl Handover Protocol (RCIHP)

3.1 System Model And Basic Concepts

The LEO satellite constellation consists of N separate planes, each with M satellites evenly distributed at the same altitude. The logical locations of all satellites can be seen in **Fig. 1**, where a satellite S_{ij} can be determined by its phase number i and its satellite number j .

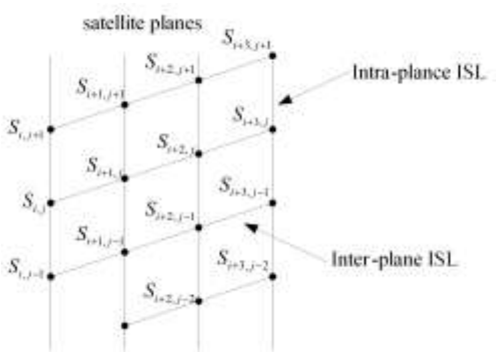

Fig. 1. Logical location of a LEO satellite network in two-dimensional plane

All satellites in the LEO satellite constellation will circulate the earth at a constant speed. While satellites in planes along side cross-seam are counter-rotating, the satellites in other planes are co-rotating. A satellite can have up to four links connecting to its adjacent neighbors, with two intra-plane ISLs in the same plane and two inter-plane ISLs in the adjacent planes [9]. When one satellite moves toward the polar area, the inter-plane ISLs have to be shut down because of physical constraint of satellite antennas at given latitude [10]. The inter-plane ISLs will be automatically turned on when the satellite leaves the polar region. Since intra-plane ISLs are static all the time, obviously we mean inter-plane ISL handover in RCIHP.

Before clarifying the ISL handover algorithm, some definitions and theorems are presented firstly as follows.

Definition 1: Satellite Load Status. A satellite load status can be classified as three levels: light-loaded, middle-loaded and heavy-loaded. In this paper, satellite load status is defined as

$$SLS = Q_{current} / Q_{total} \tag{1}$$

where $Q_{current}$ is the current queued packet size and Q_{total} is the total buffer length of one satellite. The load status of a satellite is determined by the relationship of SLS with two pre-defined thresholds α and β. If $SLS < \alpha$, then satellite is in Light Loaded State (LLS). If $\alpha \le SLS \le \beta$, then the satellite is in Middle Loaded State (MLS). And if $SLS \ge \beta$, then the satellite is in the Heavy Loaded State (HLS).

Definition 2: ISL Access Delay Time. The ISL Access Delay Time is the time during which an ISL link can't be used for transmitting packets. It is denoted as

$$T = T_{shut} + T_{guard} \tag{2}$$

where T_{shut} denotes the period during which a satellite rotates within the polar area. Because propagation delay is relatively high in satellite networks [10], an ISL may be shut down while a packet is going through on this link. T_{guard} is the guarding time which is introduced to take this factor into account. Since propagation delay is considered the most important cost factor in satellite networks [10], we define T_{guard} as

$$T_{guard} = \eta \cdot len / C \tag{3}$$

where len / C is the propagation delay of a packet. The coefficient η is introduced to model the behavior of on-board processing delay, transmission delay, etc. in a simple way.

Theorem 1: Let (p,s) represent a satellite with its phase number p and its satellite number s, as denoted in **Fig. 1**. Assume source satellite S locates at (p_s, s_s) and destination satellite D locates at (p_d, s_d). Also assume that all ISL links are identical. Then, the number of hops n_h from S to D satisfies:

$$n_h \geq |p_d - p_s| + \min(|s_d - s_s|, N - |s_d - s_s|) \tag{4}$$

where N is the number of satellites per plane.

Proof. The proof is based on the topology characterization of a satellite network. The hops from source satellite to destination satellite consist of two independent parts: horizontal hops and vertical hops. The horizontal hops and the vertical hops denote the number of ISLs the packet goes through horizontally and vertically. Since a packet can't go across the cross-seam in polar satellite networks, there is only one forwarding direction in order to achieve minimum hop path horizontally. Obviously, the minimum hop number is $|p_d - p_s|$, i.e., the phase difference between the source and the destination satellites. However, when routing a packet vertically, a satellite can communicate with two neighbors alternatively: up neighbor or down neighbor. So the minimum hops between up direction and down direction, i.e., minimum between $|s_d - s_s|$ and $N - |s_d - s_s|$, is the minimum hop number vertically. Thus, the minimum number of hops n_h is bounded by $|p_d - p_s| + \min(|s_d - s_s|, N - |s_d - s_s|)$. From above-mentioned proof, we not only know the minimum hops between any two satellites, but also could infer the forwarding direction in order to achieve a minimum hop path.

3.2 RCIHP Implementation

The goal of RCIHP is to find an optimum algorithm without incurring too much rerouting attempts. In [5], the topological dynamics such as when ISL links will be shut down and when the ISL links will be turned on again is systematically analyzed. This knowledge can be fully utilized when forwarding a packet in satellite networks. When forwarding a packet, there are two cases that will exclude a specific link as a part of a forwarding path. The first case is that the ISL link is closed at the moment, which is trivial. The second case is that the link will be shut down in a short time, which means that the ongoing traffic might be dropped on its half way to the next hop with high probability. The time interval should be in proportion to the propagation delay in that the prorogation delay is the main delay factor in satellite networks [7]. Therefore, we don't need to reroute because the down links and to-be-down links are not part of forwarding path and rerouting caused by handover is deeply controlled.

At the same time, link load status should be considered as another important factor when forwarding a packet. Topology information obviously is not enough to decide how to route a packet alone. To avoid ISL congestion, RCHIP utilizes SLS in Definition 1 as a factor to make forwarding decisions.

The RCIHP can be divided into three phases: Initial Topology Distribution Phase (ITDP), Satellite Link Status Notification Phase (SLSNP) and Packet Forwarding Phase (PFP). In ITDP, all satellites will distribute their initial positions to their adjacent neighbors. Since ITDP message exchange will only occur during initialization phase, it will not incur too much signaling overhead and the signaling cost can be ignored compared to overhead caused by rerouting protocol. Link status notification message is introduced to notify satellite's link load status to its neighbors, which can be used to distribute traffic fairly in the entire satellite network. The time when satellites exchange their link status information is closely related to the traffic load. During PFP, a packet is routed based on the satellite network topology and satellite link load information.

3.2.1 Initial Topology Distribution Phase (ITDP)

An ISL will be shut down under two circumstances [5]. The first one is that when a satellite enters into the polar region and the other is the neighbor enters into the polar region. Under both conditions, an ISL involves a handover. Thus, during PFP in order to avoid using the will-be-shutdown link we must have a clue of neighbors' current positions and their moving directions. Initial topology distribution phase just servers this purpose. Initially, all satellites will distribute their initial positions information and moving directions to their four neighbors (two intra-phase neighbors and two inter-phase neighbors). Once a satellite receives its neighboring information, it can infer when the related two ISLs will be shutdown. Note that this phase will only occur in the initialization stage and the signaling overhead can be ignored.

3.2.2 Satellite Link Status Notification Phase (SLSNP)

During ITDP, we get the topology information of neighbors and the time when a specific link will be shutdown. To avoid congestion, the ISL status must be considered. At the stage of SLSNP, when an ISL enters into MLS, it will notify its related neighbor that there is a diminution in processing capacity and the neighbor should slow down transmission to avoid total congestion. So the neighbor will trigger the load balance policy by forwarding only part of traffic. When a satellite enters into HLS, it means it has no more processing capacity and then notifies its neighbor of the status. The neighbor will choose an alternate path to forward the traffic. Once the satellite's link load status is updated, it will notify the corresponding neighbor.

3.2.3 Packet Forwarding Phase (PFP)

The PFP is the central part of RCIHP. At this stage, every packet will be routed independently based on the network's topology and its link load status. Assume S_s is the source satellite and S_d is the destination satellite. Also let S_c denote the current satellite that will perform the routing decision. The relative positions of all these satellites are shown in **Fig. 2**. The packet forwarding procedure works as follows.

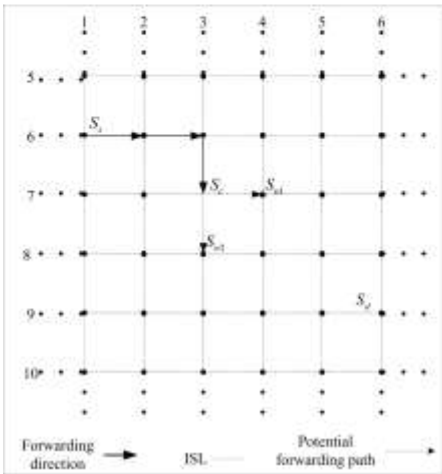

Fig. 2. Example of PFP for minimum hop paths

1) If $S_s = S_d$, i.e., S_c is the destination satellite, then the packet has reached its destination network. It will be sent to the receiver on the earth.
2) If S_c is in the polar region, then the next hop satellite must be in the same plane. To achieve a minimum hop path between S_c and S_d, apply Theorem 1 to satellite pair (S_c, S_d). Then the next hop in the same plane that will lead to minimum hop path is chosen and the packet is forwarding to the chosen next hop.

3) If S_c is not in the polar region, the next hop satellite will be in the same plane or different plane. It means that left neighbor or right neighbor will probably be chosen as the next hop satellite. To get a minimum hop path between S_c and S_d, apply Theorem 1 to (S_c, S_d). Because satellite networks have a symmetric topology, neighbors in the same plane or neighbors in the adjacent plane may be candidates for next hop satellite. But there are three situations prevent us from choosing inter-ISL neighbor as the next hop router. Firstly, if S_c is approaching the polar region, then all inter-ISLs connected with S_c will be shut down in a short time. If it is in its ISL Access Delay Time Duration, the neighbor can not be the next hop satellite. Secondly, if the inter-plane neighbor chosen by Theorem 1 is approaching the polar region and in its Access Delay Time Duration, it can't be the next hop satellite either. Lastly, if the link between S_c and its neighbor is full loaded, i.e., in its HLS which we get during SLSNP, the inter-plane neighbor can not be the next hop satellite. If either of above three conditions holds, we can only choose the neighbor in the same plane as the next hop satellite.
4) Now, both inter-plane neighbor S_{n1} and intra-plane neighbor S_{n2} as denoted by **Fig. 2** can be next hop satellite. Generally, we have a preference of inter-plane neighbor S_{n1} to intra-plane neighbor S_{n2} because inter-ISL may be shut down and intra-ISL is permanent. And according to Theorem 1 the vertical hops and horizontal hops are independent and to reach a destination satellite we must go through a minimum number of satellites in both directions, so giving preference to the horizontal hops is feasible. Then we choose the next hop based on the load status of all viable neighbors and forward the traffic to the next hop.

4. Simulation Results and Analysis

To evaluate the performance of the RCIHP, an OPNET simulation has been set up. The Iridium satellite system [11] is adopted as simulation scenario which is shown in **Fig. 3**. The Iridium constellation has 66 satellites distributed into 6 planes and has a system period about 100 minutes. Each satellite is equipped with four ISLs, including two intra-plane ISLs and two inter-plane ISLs, which are shut down when the satellite latitude exceeds 60 degrees. The simulation time lasts for 5,000 seconds which is longer than half a system period of the Iridium system (as the topology is symmetrical, which means half a period is enough for the handover simulation). In all experiments, the capacity of all User Data Links (UDLs) and the ISLs are set to 512Kbps. For traffic generation, homogenous UDP traffic is adopted throughout the simulation and two different packet sizes have been utilized. Their average packet sizes are equal to 512 Bytes and 1024 Bytes respectively. And the intervals between packets are all set to 20ms. These two packet size are selected intentionally since these two types of traffic load occupy 40% and 80% of ISL link's bandwidth.

The performance of RCIHP is evaluated in terms of end-to-end delay, number of IP hops and IP packet dropped probability. To clarify the algorithm's performance, it is compared against the widely used Dijkstra's algorithm (DA) [12]. The choice is such performance is explained as follows.

As mentioned above, network performance will be impacted from four aspects (i.e. the routing signaling overhead, packet drop rate, end-to-end delay performance, average routing hops). As routing signaling overhead incurred by ISL has been investigated carefully **[8]** and there is no signaling overhead incurred in RCIHP, we don't investigate this problem. Consequently, in the simulation section the performance of RCIHP is demonstrated from three aspects (i.e. packet drop rate, end-to-end delay performance, average routing hops) . Moreover, as our protocol handles the ISL handover problem from a different angle, we compare the performance of our protocol to Dijkstra's algorithm.

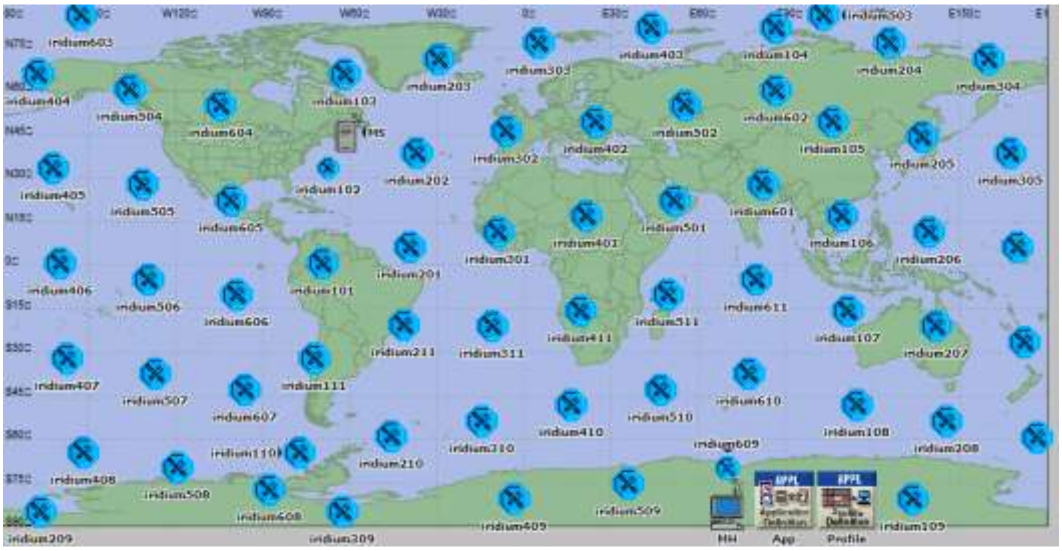

Fig. 3. Simulation model

It can be seen from **Fig. 4** and **Fig. 5** that the number of hops of RCIHP almost coincides with Dijkstra's algorithm. **Fig. 4** denotes the numbers of hops between two ground terminals which are covered by Iridium203 $(2,3)$ and Iridium303 $(3,3)$. And **Fig. 5** illustrates the number of hops between two ground terminals which are serviced by Iridium201 $(3,1)$ and Iridium601 $(6,1)$. For both algorithms, the number of hops parameter experiences sharp decrease and sharp increase alternately because relevant ISL link is shut down and turned on alternately. For instance, when the ISL link connected Iridium203 and Iridium303 is in a turned-on state, the corresponding hops are 3. While the ISL link is closed, a devious way must be found to route the packet, which takes an average of 5 hops, as can be seen from **Fig. 4**.

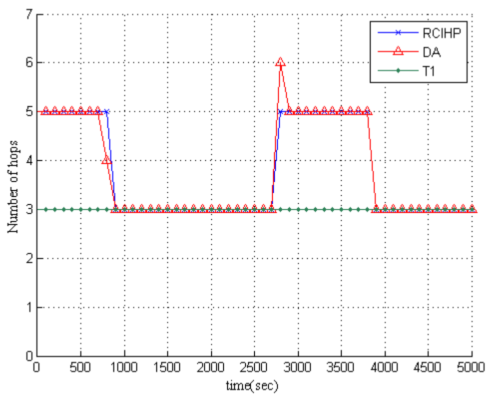

Fig. 4. Number of hops of three schemes

For both algorithms, the time the number of hops suddenly climbs up is the time an ISL handover occurs. From **Fig. 4** and **Fig. 5**, we can also learn that the number of hops generated by Theorem 1 (T1) remains constant all the time in that the theorem doesn't take ISL handover into account.

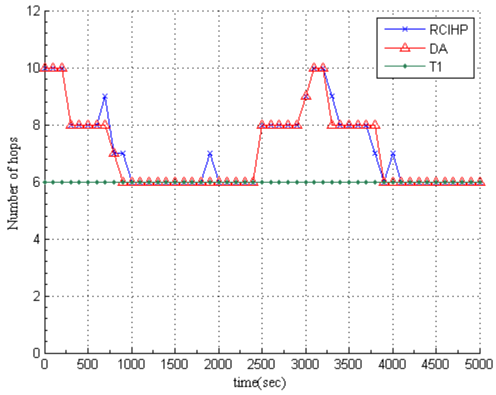

Fig. 5. Number of hops of three schemes

Fig. 6 and **Fig. 7** depict the packet loss possibility of the two algorithms under the two levels of traffic load. In this experiment, it is observed that the packet loss rate increases during the ISL handover time for Dijkstra's algorithm. However, the packet loss rate curve is smoother under RCIHP, no matter the traffic load is high or light. This phenomenon can be explained that during ISL handover, the rerouting will cause the packet delay excessively high and even result in the packet loss. However, it is not the case for RCHIP. We exclude the shutdown links or the to-be-turned-off links from our routing table in advance. So the handover doesn't affect the packet loss rate as evidently as Dijkstra's algorithm. From **Fig. 6** and **Fig. 7**, we also learn that the packet dropped rate performance of RCIHP is more distinguishable under higher load traffic than that of DA under lighter background traffic. That's because under heavy traffic load condition the load-balancing mechanism takes effect more evidently and makes the whole network less congested and reduces the packet dropped possibility.

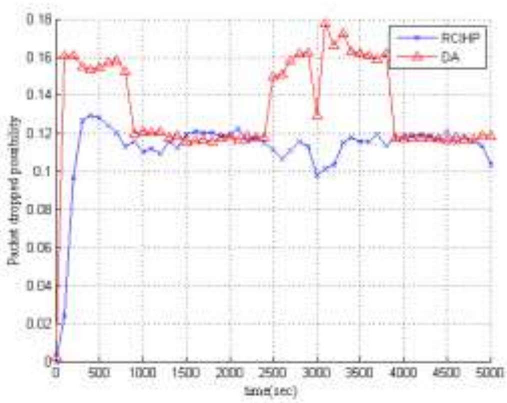

Fig. 6. Packet dropped possibility performance of two algorithms for traffic load = 40%

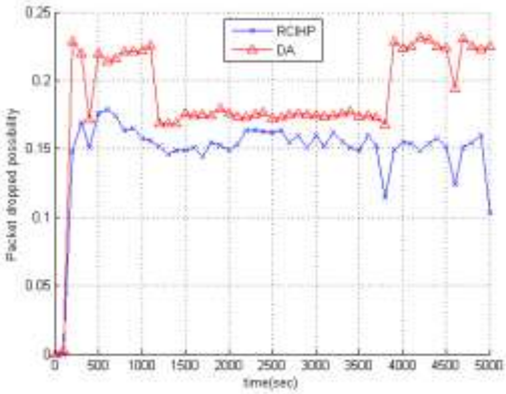

Fig. 7. Packet dropped possibility performance of two algorithms for traffic load = 80%

End-to-end delay performance is shown in **Fig. 8** and **Fig. 9** under two different load conditions. Because of the same reason as loss possibility metric, the end-to-end delay of RCIHP is superior to that of Dijkstra's algorithm.

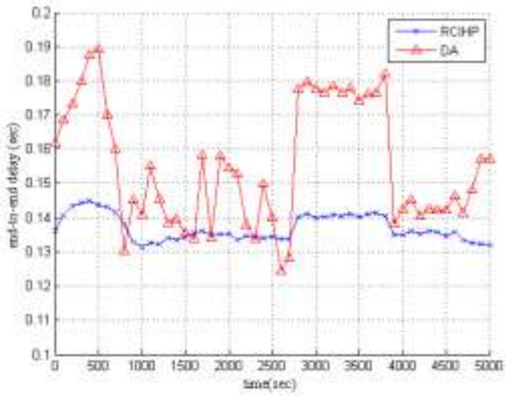

Fig. 8. End-to-end delay performance of two algorithms for traffic load = 40%

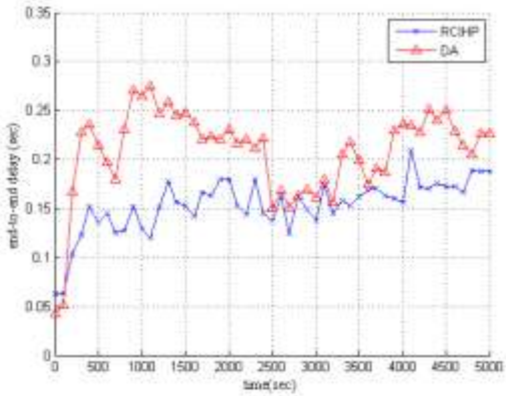

Fig. 9. End-to-end delay performance of two algorithms for traffic load = 80%

The end-to-end delay of DA is suffered from the ISL handovers, while RCIHP is more robust against the ISL handovers. With the traffic load increasing from 40% to 80%, the end-to-end delay increases for both algorithms. However, the rate of delay increasing is more slowly for RCIHP. **Fig. 9** shows the file download time performance of ATCS and three TCP variants. At all error rate levels, the performance of ATCS is superior to other TCPs. It can be observed that as bit error rate level increases the file download time of TCP degrades dramatically while the performance of ATCS is more robust than that of other flavors.

5. Conclusion

In this paper, a rerouting-controlled ISL handover protocol (RCIHP) based on topology dynamics for LEO satellite network is proposed. The protocol aims to control the passive rerouting attempts caused by ISL link handovers. Specially, we utilize network topology periodicity feature to reduce rerouting attempts actively. And we adopt a distributed forwarding policy based on link access time and link state status. As simulation results show that the protocol achieves a good performance in terms of end-to-end delay and packet loss probability. At the same time, the number of hops (path length) generated by this algorithm is comparative to Dijkstra's algorithm.

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