A Dynamic Migration Strategy of SDN Controllers in LEO Networks

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Abstract. Multiple low earth orbit (LEO) satellites form a constellation that can construct the network to achieve full coverage of the ground. However, the topology of the LEO satellite network is highly dynamic, and end-to-end transmission is a huge challenge for the LEO satellite network. As an important technology to solve the network dynamic management, the software defined network (SDN) has been introduced into the LEO satellite network. To manage the LEO network efficiently, the controllers of the SDN-based LEO satellite network can be deployed on some satellites and directly controlled by the ground base stations (GBSs). Since GBSs are static, so the controller should be migrated from one LEO satellite to another LEO satellite. Controller migration as an elastic control method plays an important role in the SDN-based LEO satellite network. Aiming at the problems of low migration efficiency and high migration cost in existing migration schemes, we propose a dynamic migration strategy of the controller. First, we analyze the load composition of the controller, and construct a load function, set the trigger factor to determine the load imbalance. Then, we determine the migration target and establish a migration efficiency model, and consider the load balancing rate and migration cost to determine the migration switch and the migration controller. Finally, by setting migration triplets to complete the migration mapping, to achieve efficient controller migration in the LEO satellite network. Simulation results show that this strategy can effectively reduce the controller response time, reduce the migration cost, and improve the controller throughput.

Keywords: Low earth orbit satellite · Dynamic migration · Controller · Software-defined network

1 Introduction

With the rapid development of communication technology, the Internet has penetrated all areas of human daily activities and has become an infrastructure for human daily and industrial production. The rapid deployment and application of 5G have brought tremendous changes to the human lifestyle, at the same time, it has a huge impact on economic, political, and military activities [1]. Due to the influence of geographical, population density, natural environment, and other factors, the basic network with wired as the backbone network has achieved full coverage in densely populated areas, however,

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it is impossible to establish base stations or access points in many areas restricted by geographical conditions, such as in the air, oceans, deserts, deep mountains [2]. In many remote areas or areas with sparse populations, it is difficult and expensive to establish base stations. Besides, in the face of natural disasters (such as typhoons, mountain torrents) or emergencies (such as terrorist attacks, riots), the networks are extremely susceptible to damage, which will cause the network connection to be interrupted. The satellite communication network is not affected by geography and is a supplement to the ground communication system, so it is widely used in areas where the ground communication system is not easy to cover or where the network construction cost is high [3]. In recent years, satellite communications have aroused great attention from academia and industry.

Satellite networks have significant advantages, such as wide-area coverage, full-time and -space interconnection, and multi-satellite coordination, which have received great attention in terms of the global network. According to the satellite orbit height, satellites can be divided into geostationary earth orbit satellites (GEO), medium earth orbit satellites (MEO), and low earth orbit satellites (LEO) [4]. The orbital altitude of GEO is about 35786 km, and the orbital altitude of the LEO satellite is ranging from 500 km to 1200 km. The round-trip transmission delay of GEO and LEO are in the range [239, 278] ms and [8, 11] ms, respectively [5]. As we all know, the quality of service (QoS) of the communication system is very sensitive to transmission delay, so LEO has a stronger advantage in communication. However, LEO satellites move at high speeds in space, so ground equipment must frequently hand over the access satellites, but frequent satellite handover is a very serious challenge for network communications. To solve this problem, routing algorithms of LEO and software-defined satellites network are widely studied. In [6], Xiao et al. proposed the LEO satellite network capacity model which to value the influence of topology and routing strategy on throughput capacity. In [7], Chen et al. studied the distributed congestion avoidance routing algorithm in the large-scale constellation networks and proposed the Longer Side Priority (LSP) strategy to maximize the path searching space.

Although the routing algorithm research can help the LEO satellite network enhance the QoS of communications, the problem of the frequent handover of LEO satellites still cannot be solved. Therefore, the concept of software defined network (SDN) was introduced into the LEO satellite networks. SDN decouples the control plane and forwarding plane in switches and centralizes the control plane into the controller as the logical control center. So the network management of SDN is flexible, and the routing rules of the flow are optimal and programmable. In [8], Ling et al. designed an OpenSatNet architecture based on the SDN scheme in the satellite network and proposed an optimized forward scheduling algorithm (OFSA) to solve the multi-objective optimization problem of tasks. In [9], Zhu et al. proposed a software defined routing algorithm in the SDN-based LEO satellite network to obtain the optimal routing path by a centralized routing strategy. In SDN, the controller is the core of network control and management, so the number and deployment location of controllers have a great impact on the performance of the SDN network. In [10], Papa et al. studied the dynamic SDN controller placement in the LEO constellation satellite network and formulated the dynamic controller placement as an Integer Linear Programming (ILP). The number of satellite communications requests is proportional to users, while the distribution of ground users is uneven. Therefore, to improve the ability of the controller for managing the network, we hope that the controller will always locate at the position of the control center, which requires controllers to be able to dynamically deploy or migrate between different LEO satellites. The development of virtualization, Docker, and network function virtualization (NFV), provides solutions for the dynamic deployment and migration of controllers in the LEO satellite network.

The rest of this paper is organized as follows. Section 2 is a problem statement. Section 3 is to derive our prediction approach, and perform some simulaitons and i analyze the simulation resutls. Finally, we concluded our works in Sect. 4.

2 Problem Statement

The space-ground integrated network (SGIN) consists of satellites and ground base stations(BSs), as Fig. 1 shows. In the SGIN, the satellites move around the earth at high speed along their orbits, so satellites cannot continuously cover a certain ground area, the satellite-ground links are dynamic. The LEO satellite constellations are highly concerned and can provide continuous service to terrestrial users by switching the access LEO satellites.

The SGIN is formed by connecting satellites to the ground and satellites to satellites. The space-based network is mainly composed of satellites in the air; the air-based network is mainly composed of helicopters; the ground-based network is mainly composed of fixed, mobile nodes, ships on the ground, and so on.

SDN is a new type of network architecture system, which supports control and data plane resolution, and has the characteristics of centralized control, making the bottom layer equipment transparent to the upper layer applications. In response to the problems in the SGIN, we apply SDN technology to it, which brings the following advantages to the entire SGIN: (1) Reduce the cost of network equipment maintenance. In the existing network, the control and data forwarding functions of the network equipment are closely coupled, and the design and development of the software and hardware of the equipment depend on different manufacturers, making the maintenance cost of the equipment higher. SDN solves the problem of control and data plane, and provides a unified and open programming interface, which reduces the cost of network equipment maintenance and brings great convenience to on-board equipment; (2) Improve the centralized control capability of the network. In the traditional network, the different hardware and software of the devices, make the equipment in the network is independent. In the traditional equipment, because of different hardware and proprietary software of manufacturers, makes the equipment in the network independent, and the equipment is heterogeneous, and the management compatibility is poor. Under the open architecture of SDN. (3) The SGIN can better adapt to new business needs. SDN has a unified and open programming interface, which enables the design of the controller to adapt to the underlying business requirements, without having to operate each device independently, making the network more convenient to adapt to new business requirements. (4) Enhance the safety and reliability of data transmission in the network. SDN can configure different control strategies for different flows to achieve multi-granularity network control capabilities, enhancing network security and reliability.

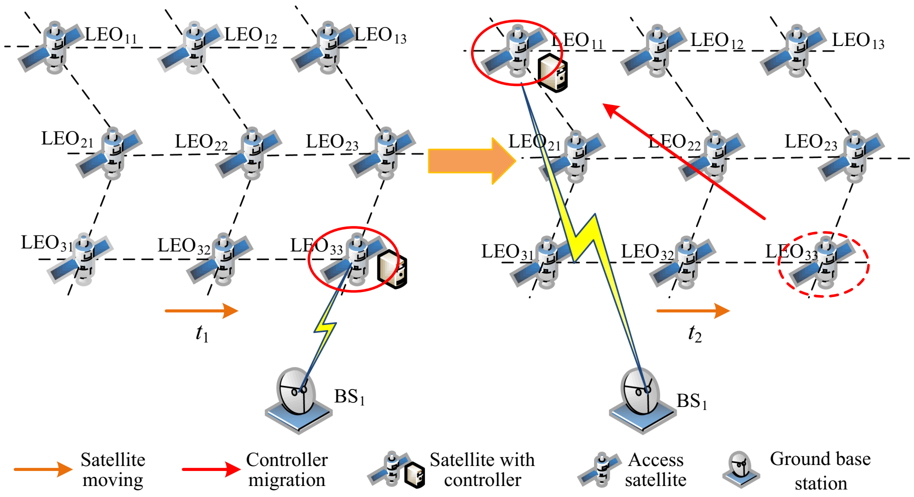

Fig. 1. The controller migration in SDN-based SGIN.

The SDN controller can obtain all the information from the data plane and construct a global view of the network, and the open northbound interface can realize rapid and automatic configuration according to different dynamic needs in the network, which meets the flexible and changeable characteristics of the world network [10]. The SGIN is composed of a space-based network and ground network, that is, a large-scale hierarchical network. According to the distance between the satellite and the ground, the space-based network consists of satellites. SDN architecture is also layered architecture. Corresponding to the SDN layered architecture in a multi-layer world network is an issue we need to study. The complex heterogeneity of the SGIN and the single controller's single point of failure and failure to meet cross-domain deployment requirements, so the multi-controller distributed deployment solution needs to be studied. Because of the frequent and highly dynamic characteristics of link switching in the SGINs, studying the reliability of the network requires studying the load balancing problem between controllers.

In the SDN-based SGIN, the controllers are deployed on some LEO satellites. Users on the ground are stationary relative to LEO satellites. When the controller on the LEO is far away from the users, the QoS (quality of service) for ground users will be greatly reduced. To solve this problem, we propose that moving the controller in the LEO, so that the controller will not be far away from the controller, as Fig. 1 shows.

In the LEO satellite network, the overload of the controller in LEO can be represented as

$$LS(j) = \sum_{i=1}^{n} r_i LR(i) \tag{1}$$

where $LS(j)$ is the total overload of the LEO satellite j, n represents the number of LEO satellites r_i represents the coefficient of the weight, $LR(i)$ represents the utilized state of the controller overload factor i. Assuming that the load of the controller close value of the threshold is $MAX\,(j)$, there are two situations about the controller migration:

In the SDN-based LEO satellite network, the flexibility of a dynamic SDN control plane concerning the number of controllers taking migration time constraints into account. There are two reasons for triggering the controller migration:

(1) $LS(j) \geq MAX\,(j)$ indicates that the controller has been overloaded or disconnect from the ground, so it should be migrated to the other satellite.
(2) $P(j) \leq P\min$ indicates that the signal strength between the LEO satellite with a controller and the GBS cannot meet the needs of measurement and control communication.
(3) $LS(j) < MAX\,(j),\ \ P(j) \leq P\min$ which means that the controller does not need to migrate from the current LEO satellite to other LEO satellites.

In the process of controller migration, we set the signal strength from GBS to the LEO satellite with a controller as one of the triggering conditions, the signal strength from the GBS to the satellite with a controller can be written as

$$LR(i)=\sum_{f=1}^{F_i} B_f C \Big/ B_{\max} \tag{2}$$

where B_f is the bandwidth that the satellite forwarding the data; f represents the index of the flow processed by the LEO satellite i; F_i is the total number processed on the LEO satellite i; B_f is the bandwidth of flow f; $B_{\max}$ is the maximum bandwidth that can be processed by the LEO satellite i, it is limited by the memory and backplane bandwidth on the LEO satellite i; C is the utilization rate of CPU on LEO satellite, which can be obtained by reading the status information of LEO satellite.

The controller migration cost contains the network status information that needs to be migrated from the current LEO satellite to the candidate LEO satellite, the network status information is not only the dynamic information of the LEO satellite network but also the static information of the LEO satellite network. When calculating the controller migration cost value and selecting the candidate LEO satellite, the weight factors $a_i(t)$ are mainly considered.

The ***controller migration Delay*** (η): we use migration delay as the metric that the overhead considered in the controller migration process. The controller migration overhead in time can be quantified as:

$$\eta = \sum_{i=1}^{N} a\lambda_i \tag{3}$$

where a is the weight factor; λ_i is the migration delay that transmits the static information of the LEO satellite network, and they can be calculated as

$$a = \begin{cases} 1/h_{ij}, & h_{ij} < n \\ 0, & LS(j) \geq MAX\,(j) \end{cases} \tag{4}$$

$$\lambda_i = I_i / B_{ij} \tag{5}$$

where h_{ij} means the hops from the current LEO satellite i to the candidate satellite j; I_i is the static information of the LEO satellite; B_{ij} is the minimum bandwidth between the current LEO satellite i to the candidate satellite j.

The ***switch access cost*** **(**ξ**)** is the delay that the LEO satellite as switch on the data plane accesses to the controller to reconstruct the control link. The switch reconstruct overhead can be rewritten like that

$$\xi = \sum_{i=1}^{N_j} t_i \tag{6}$$

where t_i is the duration that the LEO satellite i as switch on the data plane accesses to the controller to reconstruct the control link; N_j is the number of switches access into the controller in SDN-based LEO satellite network.

The migration cost of the controller is the issue that we should pay attention to at present. When the controller is migrated from the current LEO satellite into another satellite, the switch satellite on the transmission path needs to be re-connected to the new controller periodically to adjust the control plane of the network. The goal of the controller migration in the LEO satellite network is to minimize the response time and handover time of the controller while keeping control flow overhead low. Therefore, we apply the weighting factor to the response time in the objective function.

$$\begin{aligned} & \min\ \max(\eta + \xi) \\ & s.t. \\ & \quad C1 : a \geq 0 \\ & \quad C2 : t_i \geq 0 \\ & \quad C3 : C < MAX(j) \end{aligned} \tag{7}$$

where conditions $C1$ and $C2$ ensure that the weight factor of the candidate LEO satellite and the duration of the re-access controller is not negative. Condition $C3$ means that the candidate LEO satellite can deploy the controller. The objective function (7) is an optimization problem, we use the optimization algorithm to solve it.

Then, the controller migration step can be written as:

Step 1: Measure the signal strength between the LEO satellite with a controller and obtain the load of the LEO satellite with the controller.
Step 2: If the signal strength of the control satellite and the ground station is weakened $P(j) \leq P\min$ or the load of the current LEO satellite is high $LS(j) \geq MAX(j)$, the controller triggers the process of controller migration.

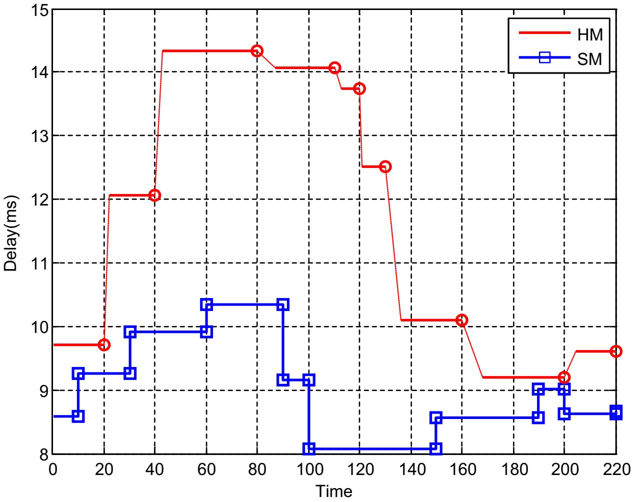

Fig. 2. The delay between the controller and the GBS.

Step 3: The controller obtains the global view of the LEO satellite network, including the current network topology, satellite memory, backplane bandwidth, etc.;
Step 4: Take all the satellites that connect to GBS directly as a set of candidate satellites, and calculate the migration cost of each candidate LEO satellite in the set, then select the LEO satellite with the least migration cost as the candidate LEO satellite with the objective function (7).
Step 5: The controller sends the network status to the candidate LEO satellite, and sends notifications to all LEO satellites as the switch in the data plane to access the candidate LEO satellite with the controller.
Step 6: Each LEO satellite as the switch access the LEO satellite that deploys the new controller.
Step 7: Return to step 2.

3 Simulation Result and Analysis

3.1 Simulation Environment

In this section, we use Matlab to simulate the proposed method, and AGI STK(Systems Tool Kit) issued to export satellite orbit data. In the simulation, all the location of the satellites are known based on data set from AGI STK. The number of satellites is 66 and we deploy satellite constellations according to the Iridium satellite system. There are two controller migration schemes, we named our method as soft migration (SM) and comparing it with the hard migration method (HM) that the controller will migrate when the GBS cannot directly communicate with the LEO satellite with a controller.

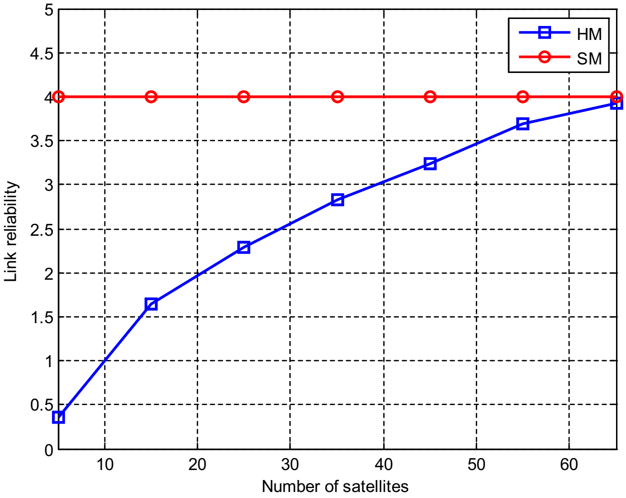

Fig. 3. The link reliability between the satellite deployed controller and the GBS

3.2 Simulation Results Analysis

Figure 2 shows the delay between the satellite deployed controller and the GBS. The red line represents the delay of HM and the blue line represents the delay with the proposed method SM. The red dotted line indicates that the link between the satellite deployed controller and the GBS is broken. In Fig. 2, we find that most of the transmit delay of HM is bigger than that of our method. The average number of handovers increases significantly. For the HM, when the signal strength of the satellite received by the GBS does not meet the communication conditions, the satellite will start the migration of the controller. Since the migration of the controller consumes time, the communication will be temporarily disconnected. For the SM, when the satellite has not reached the hard handover condition, the controller on the LEO satellite has been migrated, and the principle of SDN redirection is used to connect other switches to the controller. The satellites are connected, so the delay of the controller switching for SM is very short. This is the phenomenon shown in Fig. 2.

Figure 3 shows the link reliability between the satellite deployed controller and the GBS. The relationship between the number of satellites and the link reliability in this paper. As can be seen from Fig. 3, as the number of satellites increases, the link reliability of the network increase for the HM method, but the line is stable for the SM method. With the increasing number of satellites, then there are a large number of alternative satellites as the controller, so the deployment position of the controller migration between satellites will be frequent. The link reliability increasing with the number of satellites. For the SM, we always choose the appropriate satellite as an alternative satellite, so the links between satellite and GBS are reliable.

Figure 4 shows the mean delay between the satellite deployed controller and the GBS. The average delay is reduced to the lowest value. Continuing to deploy controllers, latency began to show an upward trend. This is mainly because the end-to-end delay of the network is mainly the delay between the controller and the switch. When there are a little number of controllers and switches, the shortest connection path between the switch and the controller in the network is always long, resulting in network control delay with the number of controllers increases, the distance between the controller and the switch begins to decrease, and the average control delay decreases continuously until the controller is migration.

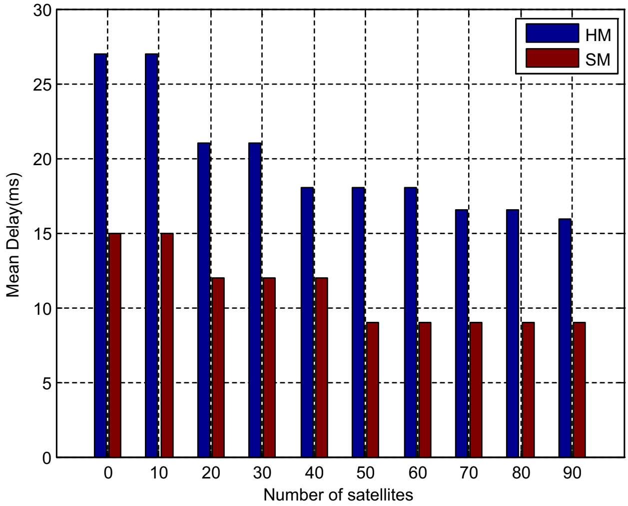

Fig. 4. **The** mean delay between the satellite deployed controller and the GBS

4 Conclusions

The architecture of the SDN enhances the flexibility of the satellite network and provides compatibility of multiple networks. The LEO satellite SDN-based network, which combines the SDN and the satellite network, is an important part of the future 5G network. However, the current LEO satellite SDN control strategy has the problem that a large amount of control information brought about by frequent handovers affects the network communication quality. Considering the problem of link stability between switches and controllers in LEO satellite SDN-based networks, we studied the migration strategy of controllers migrated between the satellites based on the soft-ware-defined network in the LEO satellite network.

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