An Improved Routing Strategy Based on Virtual Topology in LEO Satellite Networks

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Abstract. With the increasing scale of low Earth orbit (LEO) satellite networks, the satellite network topology may become more and more complex. In order to cope with local congestion and link disruption with the aid of path planning, a virtual topology based improved routing (VTIR) scheme is proposed, which can be considered as a kind of node feedback routing (NFR) To be specific, in the proposed VTIR scheme, the orbit-period is divided into time slices, and the dynamic topology is also converted into a static topology. Moreover, both queue buffer state feedback and connection state feedback are considered in routing-path computation, resulting in that the link cost may be determined by a combination of distance, congestion, and link state. Simulation results show that compared with the conventional snapshot scheme, the proposed VTIR scheme can alleviate local congestion by extending traffic to idle links, without increasing packet loss rate.

Keywords: LEO satellite networks · Virtual topology · Queue buffer · Link cost

1 Introduction

Nowadays, with the widespread application of the internet and high-speed development of space technology, satellite network has played a crucial role in the mobile communication networks [1]. Low earth orbit (LEO) satellite networks, represented by Iridium NEXT [2] and Starlink [3], are designed to supply global coverage and real-time services and contribute to the development of space-ground integrated communication systems [4]. It is suitable for the networks which has wide coverage because it can overcome the problem of long distance and desolate terrains (deserts, oceans, forests, etc.) [5]. Routing strategies are at the core of communication networks [6]. Due to the differences between LEO satellite networks and terrestrial networks, like topology dynamic, LEO satellite networks are difficult to adopt mature routing technologies in terrestrial networks. Meanwhile, the uneven distribution of global services poses significant challenges to satellite communications, such as severe link congestion.

Scholars have proposed a large number of algorithms for the feature of satellite networks, which can be categorized as the Dynamic routing algorithms, virtual node

Q. Wu et al. (Eds.): WiSATS 2020, LNICST 357, pp. 240–250, 2021.
https://doi.org/10.1007/978-3-030-69069-4_20

(VD)-based routing algorithms, and virtual topology (VT)-based routing algorithms. In the Dynamic routing algorithms, the real-time topology can be obtained by exchanging network state information. In [7] and [8], a location-assisted on-demand routing (LAOR) scheme was designed, which can distribute traffic to multiple paths. In the virtual node-based routing algorithm, the Earth's surface is sliced into several regions, each of which is assigned a fixed logic address. Satellites closest to the center of the region have the same logical address as the region. IP-based routing was proposed in [9], which divided the ground into super cellular and cellular, and satellites near the center of cellular were regarded as coverage than cellular. In [10] Ekici proposed a distributed routing algorithm (DRA), which constructed the virtual node by using the orbital plane and the number of satellites. The virtual node-based algorithm conceals the mobility of satellites and is highly adaptable. However, this approach requires a strong regularity of the constellation topology [11]. The virtual topology-based algorithm, which utilizes the periodicity of satellite movement, divided the satellite network period into a series of fixed time slice. Within each relatively small time slice, the satellite's dynamic topology can be considered either as a fixed topology or virtual topology (VT) [12]. This strategy was first proposed by Werner, who separated the dynamic topology of the satellite in a system cycle into a series of static topologies, routing problem can be transformed into virtual path routing calculation under static topology [13]. In [14], a novel routing algorithm based on virtual topology snapshot was proposed and it inherits the advantage of a lower delay in topology snapshot as well as solves the problems of poor robustness and adaptability. Gounder defines the static topology as a snapshot, then every change of inter-satellite links (ISLs) regarded as a new snapshot [15]. Moreover, in [16] and [17], the virtual topology models were used to design and evaluate the algorithm.

Virtual topology-based routing algorithms can convert dynamic topology to static routing, simplifying the conditions for designing routing algorithms and has lower requirements on the processing capability of satellite. However, it has poor adaptability to link failure and congestion, and too much time slice demands more memory space. Focus on these limitations, this paper proposed a node feedback routing (NFR).

The rest of this paper is organized as follows. In Sect. 2, the system model for the routing algorithm has been described. In Sect. 3, the detail of NFR is presented. The simulation results are shown in Sect. 4. Finally, the conclusions are given in Sect. 5.

2 System Model

In LEO satellite networks, the topology changes regularly and repeats periodically, and the number of nodes and constellation structure are usually kept constant. Therefore, the topology of the satellite network is usually represented by an undirected graph. Satellite operational cycles are divided into smaller time slices, with each time slice representing the current satellite network topology. Figure 1 shows the discrete satellite cycle.

Assuming the satellite operation cycle is T, the dynamic network topology is considered as a periodically repeating series of n topology time slices separated by step width $\Delta t = T/n$. Each of the time slices at $t = [k\Delta t, (k+1)\Delta t](k = 0, 1, 2...)$ can be regarded as fixed, which is represented as a graph $G(k) = (V, E(k))$, where $V = \{1, ..., N\}$ is the constant set of nodes and $E(k)$ represents the set of the undirected link $(i, j)_k$ between

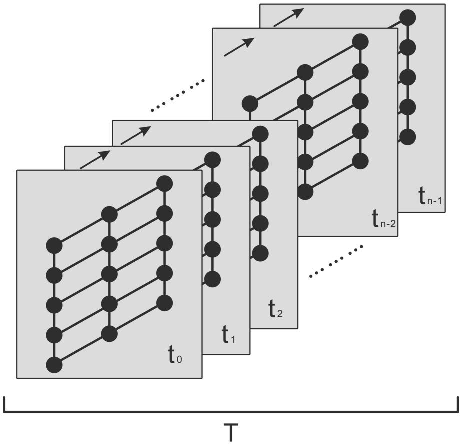


Fig. 1. Discrete-time topology

neighboring nodes i and j, existing at $t = k\Delta t(k = 1, 2, 3...)$. In this paper, the least delay routing is used for the algorithm so that the link cost $C_{i,j}(k)$ is mainly determined by node distance.

In each time slice, the Dijkstra algorithm is used for path planning for all satellites in the static network topology to calculate the shortest path. All satellites only need to store routing tables and switch them at specific times.

3 Analysis of Algorithm

3.1 Conventional Static Routing Based on VT

The VT-based algorithm adopts the model described in Sect. 2. The routing table for each time slice is computed centrally and uploaded to the satellite, thus increasing the simplicity and stability of routing. For the selection of the time slice interval, the first important factor is that the physical topology of the satellite network at the current time should be accurately reflected. Second, the link cost should satisfy formula (1) as much as possible, that is, the variation in link cost within the time slice of the adjacent time should be as small as possible.

$$\frac{C_{i,j}[(k+1)\Delta t] - C_{i,j}(k\Delta t)}{C_{i,j}(k\Delta t)} << 1, \forall (i,j)_k \in E(k) \tag{1}$$

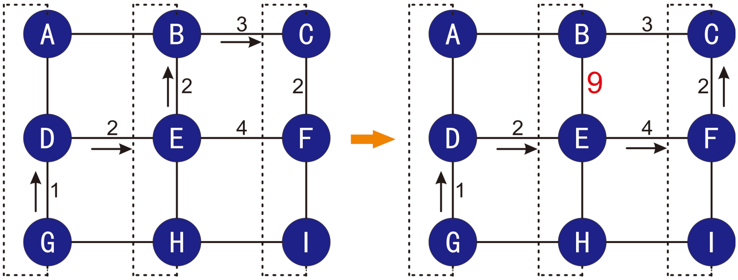
However, the static routing table stored in the satellite is unable to sense sudden changes in the network. When there is link congestion or failure, it cannot respond in a timely manner, resulting in a drastic degradation of network performance. Also, in order to achieve smaller changes in link cost, the duration of time slices should be as small as possible, which conversely requires more storage space. However large time slice interval do not accurately reflect the network topology, thus affecting network performance. Therefore, the length of the time slice is a considerable problem.

3.2 VT Based Node Feedback Routing

An improved algorithm is proposed in this paper mainly focus on the above limitations, named VT based Node feedback routing (VTNFR), which has the following features: (1) The static routing table is no longer stored on the satellite, but the adjacent matrixes, which stores the distance between each satellite nodes and changes dynamically according to the change of node resources; (2) proposed a node feedback mechanism including queue buffer feedback and link interruption feedback, where routing selected based on consideration of not only distance but also queue buffer congestion state and link interrupts.

In the network shown in Fig. 2, assuming that the source node is G and the destination node is C, the routing protocol needs to find the shortest path from node G to node C. Suppose that there are two alternative paths as follows, they are

$$P1 = \mathrm{G, D, E, B, C}\ ,\ P2 = \{G, D, E, F, C\} \tag{2}$$



(a) (b)

Fig. 2. Shortest path diagram

If the distance is used as the link cost only, then the distance of two links is.

$$d_{p1} = 1 + 2 + 2 + 3 = 8,\ d_{p2} = 1 + 2 + 4 + 2 = 9 \tag{3}$$

$$d_{p1} < d_{p2} \tag{4}$$

The final shortest path is

$$P1 = \{G, D, E, B, C\} \tag{5}$$

As shown in Fig. 2 (a). If congestion occurs on the link between node E and node B, assuming the congestion size is 50% of the queue buffer, that is $Cachestate = 50\%$ (assuming the queue buffer size $CacheSize = 100Kbit$, the ISLs transmission rate $V = 5\,Mbps$), then the queuing time will reach

$$T_{queue} = \frac{CacheSise * CacheState}{V} = 10\,ms \tag{6}$$

Due to the distance is used as the link cost, the delay needs to be converted into a distance. According to the following formula

$$d = T_{queue} * c = 3 \tag{7}$$

Where c is the speed of light, and the value is simplified, which means that the distance from node E to node B needs extra propagation. Then, the cost of the whole path of $P1$ is modified to

$$d_{p1} = 1 + 2 + 2 + 3 + 3 = 11 \tag{8}$$

$$d_{p1} > d_{p2} \tag{9}$$

Obviously, the shortest path from node G to Node C is

$$P2 = \{G, D, E, F, C\} \tag{10}$$

As shown in Fig. 2 (b). Formulas (6) and (7) are combined as follows

$$L_{queue} = [\frac{CacheSise * CacheState}{V}] * c \tag{11}$$

Where L_{queue} represents the link congestion cost, the queue buffer size is expressed as *CacheSize*, *CacheState* represents the occupation ration of the queue buffer area, V represents the link transmission rate, c represents the transmission speed of information in space, that is, the speed of light.

Based on the above theory, the link cost between different nodes is no longer fixed. The convention shortest path algorithm based protocol treats the link cost as unidirectional, that is

$$L_{\cos t}(A, B) = L_{\cos t}(B, A) \tag{12}$$

The Eq. (12) indicates the link cost from node A to node B consistent with the link cost form node B to node A. However, in this paper, the formula needs to be modified as follows based on the existence of the above mechanism

$$L_{\cos t}(A, B) \neq L_{\cos t}(B, A) \tag{13}$$

This is because the congestion levels in the queue buffers of node A and node B are not the same. Equation (13) is equal only if there is no congestion between node A and node B.

According to the above mechanism, the generation of the shortest path can be made more flexible and the protocol has stronger adaptability to the congestion situation which can distribute the traffic of the congestion to other relatively idle links.

If the link between the current node and the next node fails during the communication process which leads to data loss. This problem can be addressed by the periodic feedback mechanism. The link in this direction has been broken if no feedback is received within the specified time, then the link cost is modified to infinity in the adjacent matrixes, and the interrupted link can be avoided when calculating the routes. The algorithm flow chart is shown in Fig. 3.

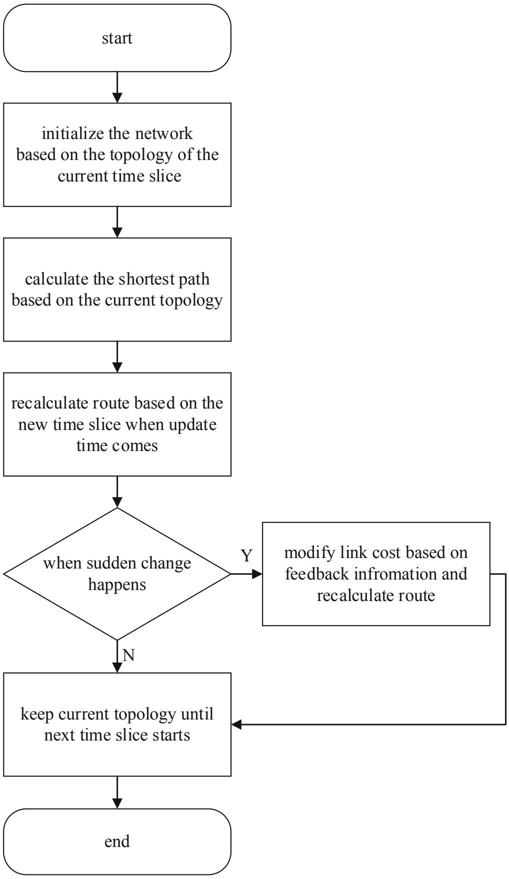


Fig. 3 Algorithm flowchart

4 Simulation and Results

4.1 Simulation Scenario

Simulation results are achieved by superb network simulation software OPNET and the network model built in OPNET is shown in Fig. 4. Referring to the Iridium system, there are 66 satellite nodes evenly distributed in 6 orbits, so that the relative position between the satellites remain essentially the same (ignoring orbital perturbations) and the connections between each satellite can be considered fixed. The altitude of orbits is 780 km and the orbit inclination angle is 86.4°. Meanwhile, each satellite node has four ISLs. Since the satellites on both sides of the reverse seam without ISL, which only have three ISLs.

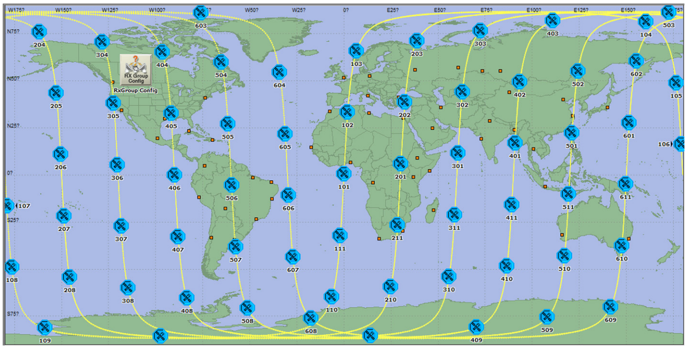


Fig. 4. Satellite network topology

4.2 Time Slice Interval Determination

To determine the suitable time slices interval, network topology structure under different time slice intervals is selected for simulation. In this paper, $\Delta t = \{60\,\mathrm{s}, 90\,\mathrm{s}, 120\,\mathrm{s}, 150\,\mathrm{s}, 180\,\mathrm{s}\}$ is selected for simulation respectively, the network packet loss rate at different time slice intervals is compared. The packet loss rate indicates the reliability of the network [18] The simulation results are shown in Fig. 5.

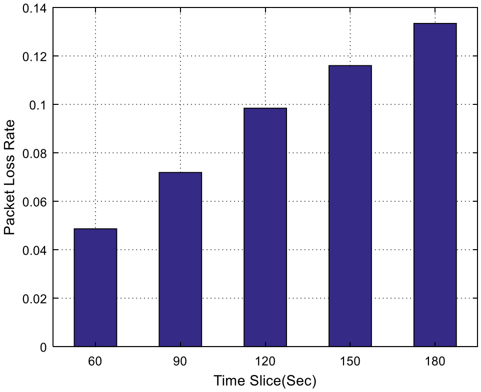


Fig. 5. Different time slice packet loss rate

As is shown in Fig. 5 above, the packet loss rate increases as the time slice interval increases. The smaller the time slice interval, the more accurate the satellite network topology reflected, which means the lower packet loss rate. However, frequent time slice switching causes short-term transmission interruptions and degrades the stability of routing. In addition, due to the large number of time slices, the requirements for storage and computing power are high. It can be seen from the figure that the packet loss rate at the $\Delta t = 120\,\mathrm{s}$ is about 10%, while the $\Delta t = 60\,\mathrm{s}$ is about 5%, a difference of about 5%. Meanwhile, the number of the time slices at the $\Delta t = 120$ s is half the number of it at the $\Delta t = 60$ s, the requirements for storage and computing power will be half and the routing will be more stable. Considering this, the time slice interval $\Delta t = 120$ s is selected in this paper.

4.3 Evaluation Result of Delay, Path Switch, and Packet Loss Rate

The NFR was compared with the conventional snapshot algorithm. The simulation time was 2 h, the source and destination nodes were selected, and the satellite packets were sent at an interval of 0.05 s. To simulate the local for the congested environment, the generation time of burst traffic is 600 s and the duration is 20 s. The results are as follows.

In Fig. 6, the delay of NFR during congestion is lower than that of the snapshot algorithm. This is because when the network is congested, the snapshot algorithm will transmit packets consecutively on a precomputed path and will not be able to sense the queue buffer congestion, which causes a continuous increase in queue buffer, resulting in a dramatic increase in packet delay. NFR can switch to another idle path in time, thus avoiding the accumulation of data packets in the queue buffer area. At the same time, it can be seen that NFR and the snapshot algorithm have almost the same delay since the basis of the NFR is the snapshot algorithm. Figure 7 shows a schematic representation of path switching, and the ordinate is the satellite number. The next hop for the source node is node 10 and the standby next hop is node 11. It can be seen that the snapshot algorithm does not switch the path when congestion continues to occur. The NFR will promptly switch paths to an idle path 1 s after getting congestion information. When the congestion is cleared, the NFR will switch back to the original path again. The performance of the improved algorithm is verified by simulation to achieve the effect of reducing local congestion.

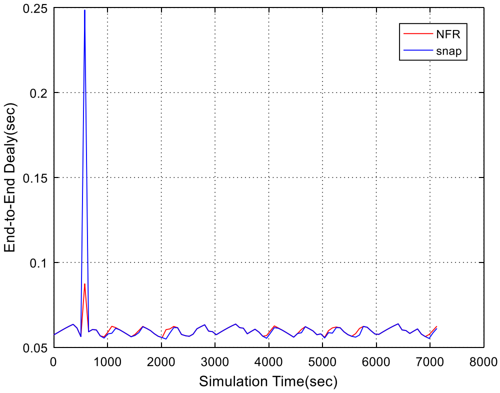


Fig. 6. End-to-end delay

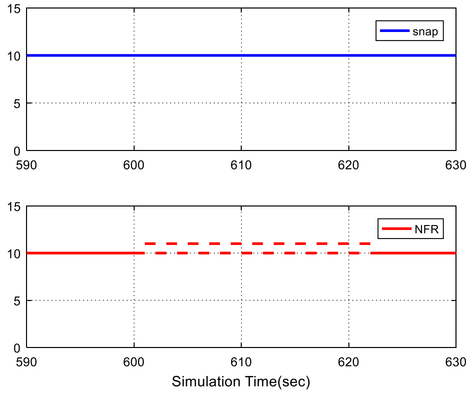


Fig. 7. Path switch

Figure 8 validates the effectiveness of NFR for link disruptions in the polar regions. The results indicate that the snapshot algorithm has an average packet loss rate more than the NFR when the network is stable. The main reason is that the satellites send packets according to the current shortest path during a time slice period, and when the satellites move to the polar region, the inter-satellite link will be closed, but the static routing table calculated according to the current topology cannot detect the link disconnection and is still follows the shortest path, ultimately resulting in a packet loss. The NFR can detect the link on–off state by the link feedback mechanism, and then switch to the normal path to avoid packet loss.

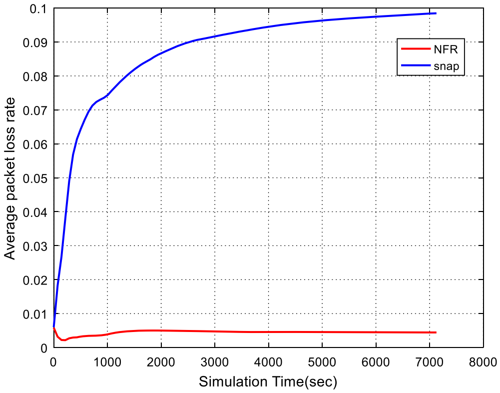


Fig. 8. Packet loss rate

5 Conclusion

In this paper, an improved routing based on virtual topology, called Node Feedback Routing (NFR), is proposed. NFR uses the node feedback mechanism to compute the routing table and feed the state of the queue buffer and link state to the routing protocol. Based on the above mechanism, NFR has strong adaptability to sudden network conditions caused by link congestion and interruptions. At the same time, it inherited the advantages of low end-to-end delay of virtual topology-based routing algorithms.

Acknowledgements. This work presented was partially supported by the National Science Foundation of China (No. 91738201 and 61772287), the China Postdoctoral Science Foundation (No. 2018M632347), the Natural Science Foundation for Jiangsu Higher Education Institutions (No. 18KJB510030 and 16KJB510031), and the Key University Science Research Project of Jiangsu Province (No. 18KJA510004).

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