Modeling and Routing for Predictable Dynamic Networks

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ABSTRACT
The topologies of predictable dynamic networks are continuously dynamic in terms of node position, network connectivity and link metric. However, their dynamics are almost predictable compared with the ad-hoc network. The existing routing protocols specific to static or ad-hoc network do not consider this predictability and thus are not very efficient for some cases.

We present a topology model based on Divide-and-Merge methodology to formulate the dynamic topology into the series of static topologies, which can reflect the topology dynamics correctly with the least number of static topologies. Then we design a dynamic programing algorithm to solve that model and determine the timing of routing update and the topology to be used. Besides, for the classic predictable dynamic network—space Internet, the links at some region have shorter delay, which leads to most traffic converge at these links. Meanwhile, the connectivity and metric of these links continuously vary, which results in a great end-to-end path variations and routing updates. In this paper, we propose a stable routing scheme which adds link life-time into its metric to eliminate these dynamics. And then we take use of the Dijkstra’s greedy feature to release some paths from the dynamic link, achieving the goal of routing stability. Experimental results show that our method can significantly decrease the number of changed paths and affected network nodes, and then greatly improve the network stability. Interestingly, our method can also achieve better network performance, including the less number of loss packets, smoother variation of end-to-end delay and higher throughput.

KEYWORDS
predictable dynamic network, topology modeling, routing, Space Internet

1 INTRODUCTION
Background. Currently, the IP-based applications of ground network and space network are integrating. Building a space Internet providing IP-based services has become an important part of the future network. In fact, there have been some proposed systems taking IP technology as the basic operation mode, such as Inmarsat [25] and Iridium [19]. Meanwhile, some Internet content providers actively carry out the construction of space Internet, such as Google and Facebook [30, 32]. Google has developed the Project Loon to provide Internet access to rural and remote areas [32] and also invested the companies SpaceX and OneWeb to build space Internet [31, 35]. Facebook also announced the Internet.org Platform with other six companies, in order to bring the Internet to everybody via satellites and drones [30].

In the world of satellites, the Low Earth orbit (LEO) constellation offers significantly smaller propagation delays as well as lower signal attenuation than geostationary (GEO) satellites, therefore, the LEO constellation equipped with intersatellite link (ISL) has been considered as a good way to form a global communication environment in space [3, 19, 30–33]. As the use of ISL greatly complicates the design of system, the LEO constellation with circular polar orbits is prone to be chosen. Up to now, most proposed and only well-known practical commercial LEO constellations with ISL are based on the circular polar orbits [3, 12, 19]. And thus such constellation is considered as the classical topology of space Internet.

Space Internet has some different characteristics compared with the existing ground network. Space Internet is the network with satellite nodes permanently flying along some fixed orbits from a polar to other. In regular operation, topology dynamics of such network are predictable, including the position of satellite node, variations of the link metric and network connectivity. The position of satellite node can be correctly computed by the system parameters and running time. The satellite nodes are extremely far away from each other, and thus the propagation delay of link is so large that is in most cases taken as the link metric [1, 11, 17, 20, 29]. The metric of link interconnecting satellites in adjacent orbits (called inter-orbit ISL) also varies with its position. The metric of that link will become shorter when the satellite node is close to the polar region (above a certain latitude). Besides, the construction of that link is limited by its angular rate for tracking antenna. When an inter-orbit ISL is close to the polar region, the angular rate for tracking antenna will become so high that the ISL will be dropped [3, 12]. The link will reconnect when it flies away from the polar region. The network connectivity induced by reconnection/connection of ISL and link metric will simultaneously change along with their positions.

Topology Modeling. Up to date, there are two main methods of modeling the predictable dynamic topology. In [28, 29], the authors adopted a fixed time interval (e.g. 60s) to divide the topology of a system period (simplified DT-DVTR). Each static topology is corresponding to a routing update. But the length of the time interval is hard to be selected. A larger time interval means that a lot details of topology variations are ignored, while a smaller one means that more routing updates will be needed. And even this method may cause route loss/suboptimality when the link disconnection/reconnection occurs during a fixed time interval. Some authors [13, 15] proposed a method of dividing the predictable
topology based on the link connectivity (simplified PLSR). In this method, when a link disconnects/reconnects means that a new topology is formed. Each topology is corresponding to a time interval. In some cases, the largest time interval is 40 times of the shortest one [27]. This method will also cause some details of topology variation to be lost, e.g. the delay variation. Moreover, both existing models didn’t consider that the continuously dynamic topology can keep relatively unchanged during a period of time, and the topology during this duration should not be divided. Thus the current models could not reflect the variations of topology accurately with least number of static topologies.

With consideration of topology dynamics, we build a topology model based on the Divide-and-Merge methodology [9]. First, we divide such topology into many discrete static topologies, which can reflect dynamics of topology correctly. For merge phase, for decreasing the number of static topologies, we merge those unchanged or only slightly changed contiguous static topologies. Then we propose a dynamic programming algorithm to solve that model and determine the timing of routing updates and the topology to be used.

Routing Scheme. Since the inter-orbit ISLs close to the polar region have a shorter delay, routes between two routers are prone to concentrating at these links. However, almost all such links are the nearly disconnecting or newly reconnecting links. In this case, once the connectivity of these links changes, a lot of routing will be forced to change. Moreover, along with disconnection or reconnection of the inter-orbit ISLs, the metrics of these inter-orbit ISLs will relatively vary. The result is that they will alternately become the shortest ISL, leading to some routing switching back and forth between them. The routing thus will oscillate in the polar region (polar oscillation for short).

Compared with the routing oscillation of traditional networks [4, 22], the polar oscillation has three unique features: First, the polar oscillation will continuously occur in the polar region because the network connectivity and link metric that cause polar oscillation continuously vary with the satellite movement. Moreover, the ISLs where polar oscillation occurs constantly vary. Extremely, these ISLs are always the overloaded links. Those features are absent in the stable routing schemes of traditional Internet [4, 22] and ad-hoc network [6], and thus a new routing scheme is needed for the polar oscillation. Although some researchers have focused on the routing stability of space Internet [5, 16, 18], no researchers have realized this issue. As far as we know, we are the first group that focuses on the polar oscillation.

Based on the above topology model, we design a stable routing scheme for the polar oscillation. First, we define the life-time of link to find those links where the polar oscillation occurs. Then we considered the life-time of these links into their metrics, eliminating the relative variation of their metrics. Furthermore, we take advantages of the Dijkstra’s greedy property to decrease the number of paths sharing these overloaded links and to avoid routing (end-to-end paths) switching back and forth between them.

The experimental results show that our method can significantly decrease the number of changed paths and affected satellite nodes, thus improving the network stability. Interestingly, our method can also achieve better throughput performance, less packet loss, and smoother variation of end-to-end delays.

Organization. The rest of this paper is organized as follows. Section 2 presents the topology characteristics of space Internet. In section 3, the routing concept of space Internet is discussed. Then a detailed presentation about our topology model is provided in section 4. The stability of space Internet is deep analyzed in section 5 and the corresponding routing scheme is presented in section 6. In section 7, we present some experiments used to verify our methods. Finally, we review the related work in section 8 and draw a conclusion in section 9.

2 NETWORK TOPOLOGY OF THE SPACE INTERNET

The space Internet is a classic system of the predictable dynamic network, which provides Internet access for global users. The LEO constellation with global coverage and low latency is considered as the ideal network infrastructure of space Internet, such as Iridium, SpaceX, OneWeb [19, 31, 33]. Currently, the Iridium system is the only well-known practical commercial system to provide global services (mainly voice services), and also announced that they will build the Iridium-Next system to provide IP-based services for global users. Therefore, the Iridium-like constellation is considered as a representation topology for the analysis and simulation in this paper. The parameters of the selected system are given in TABLE 1.

2.1 Overview of Network Topology

Fig.1 shows that the Iridium-like system is seen from the North Pole. The constellation has 6 orbits, all of which intersect at the pole. In each orbit, there are 6 or 7 satellites painted in the figure. However, for the overall system, there are totally 11 evenly distributed satellites in each orbit. And all satellites predictably fly along their own orbits from one polar to the other. The time of all satellite flying a circle around the earth is called the system period, about 100min.

Each satellite is equipped with 2 to 4 ISLs. The ISL interconnects neighboring satellites within line-of-sight. Two of these ISLs (intra-orbit ISL) are used to link the ahead and behind satellite in the same orbit, while the other two (inter-orbit ISL) are used to interconnect adjacent satellites in adjacent orbits. For an inter-orbit ISL, the viewing angle for maintaining it is varying with its latitude. When an inter-orbit ISL is above a certain latitude (boundary of polar region), the angular rates for tracking antennas become so high that the inter-orbit ISL will be dropped [12]. In other words, when a satellite enters the polar region, its adjacent inter-orbit ISLs will disconnect; when it leaves the region, its adjacent inter-orbit ISLs will reconnect.

The simplified topology with only two adjacent orbits is shown in Fig.1. For simplicity, the adjacent satellites in the adjacent orbits are painted in the same horizontal direction. We can clearly get that all of intra-orbit ISLs have the same delay, and the inter-orbit ISLs disconnect in the polar region.

As shown in Fig.1, the satellites at both sides of the seam are counter-rotating. The connectivity of adjacent counter-orbiting satellites frequently changes, which puts great stress on the design of network. In practical systems, inter-orbit ISLs passing the seam are not yet implemented [12, 19]. Thus, the routing between two satellites at the both sides of the seam will go through the polar
region, e.g. the routing between satellite A and B who are very close.

2.2 Variations of Network Connectivity
Suffering from ISL disconnection and reconnection, the network connectivity constantly and predictably varies. However, the variation is regular, that is the disconnection and reconnection alternately appearing. The time intervals between two adjacent variations only have two types, namely the time from ISL disconnection to ISL reconnection, and the time from ISL reconnection to ISL disconnection. Interestingly, each kind of time interval only has a constant value. For the selected constellation, the time from disconnection to reconnection and the time from reconnection to disconnection are 162.7s and 111.3s, respectively. On average, the network connectivity is changed once per 136.8s.

2.3 Characteristics of Link Delay
In the ground network, the link propagation delay is small and always ignored. However, in the space network, any two satellites are wide apart. The propagation delay is so large that is in most cases taken as the link metric.

For the intra-orbit ISL, its propagation delay keeps constant during a system period, about 13.5ms. Meanwhile, all of the intra-orbit ISLs have a common propagation delay because every satellite is evenly distributed in its own orbit.

The propagation delay of inter-orbit ISL continuously varies with the ISL’s latitude. When the ISL resides over the Equator, the propagation delay becomes the largest, about 15ms. When the ISL is closest to the polar region boundary, the delay becomes the smallest, about 9ms. However, if the inter-orbit ISL moves into the polar region, its delay becomes infinite due to the ISL drop.

On the other hand, compared with the propagation delay the queuing delay can be directly ignored, and thus the routing computing can be independent of the queuing delay [20]. As the routing protocol design relies on the underlying topological features of the satellite network, most current routing schemes take the propagation delay as the link metric [1, 11, 17, 20, 29].

3 IP-BASED CENTRALIZED ROUTING CONCEPT
Compared with the ground network, the space Internet has continuously dynamic topologies and limited on-board resources, such as computing ability, storage, and power. The routing schemes that are implemented on the satellite or rely on exchanging network information to know the real network topology will incur a heavy overhead.

By making use of the predictability of topology, the routing table is computed in advance of the real network topology forming. For current Iridium system with circuit switching technology, the routing table is computed on a ground station. When a LEO satellite flies above the station, the satellite will get its routing tables of a future period. However, we don’t clear the detail of their current topology model and routing technology. Moreover, the routing technology of their Iridium-Next system may be still in the stage of research.

Based on this current practical system and some researches, we suppose that the routing of space Internet is also computed on the ground station. The LEO satellite will not only get its routing tables from the stations but also can use GEO satellites to relay its routing tables, as shown in Fig.2. The utilize of GEO can avoid implementing the stations in the remote area.

For this continuously dynamic network, we cannot compute the routing table of all moments, but can just compute it at some specific time points. Thus, it’s still a challenge to determine the timing of each routing update and the network topology to be used. Based on the predictability, a system period is divided into a serial of time intervals (called snapshots). The topology of each snapshot is considered as unchanged. Before the start of a snapshot, the ground station uploads the corresponding routing table to each satellite. The routing table will be implemented once the time of snapshot arrives. Then according to this routing table, the IP-based packet is forwarded hop-by-hop.

4 TOPOLOGY MODELING
In this section, we build a topology model to partition the continuously dynamic topology into a series of discrete static topologies, and determine the timing of routing update and the topology to be used.

Although the topology of space network is continuously dynamic, the topology during a period of time can still remain relatively unchanged. The routing during this duration will keep unchanged, meanwhile, the topology can be considered as unchanged and should not be divided. Based on this theory, we build the topology model with divide-and-merge methodology as follows:
1) Divide phase: we formulate the dynamic topology, and divide it into many static topologies, which can reflect the topology dynamics correctly.

2) Merge phase: we merge the contiguous snapshots whose topologies are unchanged or only slightly changed into a merged snapshot. In this case, the goal of reflecting the dynamic topology is to merge those contiguous snapshots whose topologies are unchanged or only slightly changed to decrease the number of static topologies without degrading the accuracy of modeling the network dynamics.

3) Dynamic Programming Algorithm: we design a dynamic programming algorithm to solve above model, determining the timing of routing update and topology to be used.

4.1 Divide Phase

First, we divide the system period of the dynamic network into a series of intervals (snapshots). Each snapshot has a start time and a finish time. We use the start time to identify the snapshot, and the finish time of this snapshot is also the start time of the next snapshot. The topology during a snapshot is considered to be fixed.

Let the set \( T \) denote all of the divided snapshots that have not been merged. The elements of set \( T \) are denoted as \( t_1, t_2, \ldots, t_n \), with \( t_1 < t_2 < \ldots < t_n \). \( n \) is the total number of divided snapshots. \( t_k \) is the start time of snapshot \( t_k \), which is also the finish time of its previous snapshot \( t_{k-1} \).

In the snapshot \( t_k \), the topology is considered as fixed. Thus, the duration \( t_{k+1} - t_k \) of snapshot \( t_k \) decides the accuracy of the snapshot \( t_k \) to reflect the physical topology between the time point \( t_k \) and \( t_{k+1} \). A smaller \( t_{k+1} - t_k \) can accurately reflect the topology variation, including the network connectivity variation and the link metric variation, while a larger \( t_{k+1} - t_k \) can induce much topology detail loss.

For correctly reflecting variations of physical topology, \( t_{k+1} - t_k \) is set to a very small value. During a short time \( t_{k+1} - t_k \), the topology remains relatively unchanged. The continuously dynamic topology then is divided into a series of static topologies, which can reflect variations of physical topology correctly.

4.2 Merge Phase

In this section, our objective is to merge those contiguous snapshots whose topologies are unchanged or only slightly changed into a merged snapshot. When a merged snapshot is created, a new static topology and routing update will be incurred. The routing will be updated at the start time of the first snapshot, and the topology of the first snapshot will be used. In other words, we use a new merged snapshot instead of those divided snapshots to model the continuously dynamic topology.

Compared with those divided snapshots, the larger duration of merged snapshot may increase the error of reflecting the network dynamics. While the cost brought by routing update will be decreased due to reduced number of snapshots. If we merge those contiguous snapshots whose topologies are unchanged or only slightly, both error and cost will remain almost unchanged. Thus, the goal of reflecting the dynamics correctly with least number of static topologies can be achieved by minimizing error and cost.

Formulating model. From the discussion above, we have a set of divided snapshots \( T \) containing \( t_1, t_2, \ldots, t_n \). Its subset is denoted as \( T_{i,j} \) with \( \{ t_i, t_{i+1}, \ldots, t_j \} \) indicating \( i \leq j \). Snapshots of each subset can be merged into a merged snapshot. In this case, the goal of that model is to partition the total divided snapshots \( T \) into a series of subsets with the minimum penalty. The penalty is defined as a weighted sum of:

- \( e_{i,j} \): the degree of merged snapshot \( T_{i,j} \) failing to reflect the topology variation.
- \( C_{i,j+1} \): the cost of routing update induced by a new merged snapshot \( T_{i,j} \).

Error of modeling topology dynamics. We compute an error \( e_{i,j} \) with respect to each subset \( T_{i,j} \), according to the degree of \( T_{i,j} \) failing to reflect the topology dynamics. The network topology dynamics between the time point \( t_i \) and \( t_j \) mainly consists of the link metric variation, and network connectivity variation. The network connectivity variation also includes some ISLs disconnection and reconnection. If these variations occur during a snapshot and are undetected by the model, they will cause errors. The total error \( e_{i,j} \) are defined as the sum of errors brought by ISLs reconnection, ISLs disconnection and ISL metric variation, respectively denoted as \( e^f_{i,j} \) and \( e^d_{i,j} \) and \( e^d_{m} \). And the \( w_o \) and \( w_m \) are the weights corresponding to the network connectivity variation and link metric variation.

\[
e_{i,j} = w_o \ast (e^f_{i,j} + e^d_{i,j}) + w_m \ast e^d_{i,j}
\]

Explicitly, if the ISL reconnection during a snapshot is not considered into its topology, the link resource will be under-utilized; if the ISLs disconnection during a snapshot is considered into its topology, packet loss will be incurred after the ISL breaks down; if the link metrics variation during a snapshot is considered into its topology, some shortest paths will become suboptimal.

In fact, the errors are directly caused by the routing variation. Meanwhile, the dynamics of network topology is also directly reflected in the routing variations. Thus the routing variation is a bridge between dynamics of network topology and errors. From the view of routing variation, these errors are defined as follows.

\[
e^f_{i,j} = \sum_{r=1}^{R} \frac{t_j - t_i}{t_i}
\]

\[
e^d_{i,j} = \sum_{d=1}^{D} \frac{t_j - t_i}{t_i}
\]

\[
e^{m}_{i,j} = \sum_{m=1}^{M} \frac{\|p^m_{\delta(m)} - p^m_{p_j}\|}{p^m_{\delta(m)}}
\]

In equation (2), the \( R, D, M \) represent the total number of re-connection ISLs, disconnecting ISLs and suboptimal paths during the merged snapshot \( T_{i,j} \) respectively. The suboptimal paths are mainly caused by link metric variations. The occurrence time of these instantaneous events is denoted as \( \delta(\cdot) \), which is an element of the set \( T \). The number of paths passing link \( r \) and link \( d \) at the time \( \delta(\cdot) \), are receptively denoted as \( I^r_{\delta(\cdot)} \) and \( I^d_{\delta(\cdot)} \). The impact of ISL reconnection or disconnection on the snapshot \( T_{i,j} \) is indicated as \( t_{j} - t_{i-1} \). And \( p^m_{\delta(m)} \) indicates the length of suboptimal path \( m \) at time \( \delta(m) \); \( p^m \) denotes the length of corresponding optimal path at the start time of snapshot \( j \). The relative variation between suboptimal and optimal paths is indicated as \( \|p^m_{\delta(m)} - p^m\| \).
We take use of the physical meaning of the cost to destroy the value of the first subset. Depending, we can remove the first subset and use the same strategy to remaining snapshots. If we remove the merged snapshots in nature is network topology variation from the merged snapshots related to its start time, the topology variation between of the remaining snapshots is destroyed. Sub-problems become independent, and then construct the optimal sub-problem.

4.3 Dynamic Programming Algorithm

Designing Algorithm. For above model, there may exist many solutions. Now, we design a dynamic programming algorithm to find an optimal solution with polynomial time.

When we have merged some snapshots \( T_{i_1,i} \), the sub-problem is to partition the remaining snapshots \( T_{i+1,n} \) with minimum penalty. However, the cost of routing update \( C_{i_1,i+1} \) is dynamically changing with the topologies of merged snapshots \( T_{i_1,i} \) and remaining snapshots \( T_{i+1,n} \), which causes the sub-problems are dependent. Thus, it will not satisfy the requirement of dynamic programming. We take use of the physical meaning of the cost to destroy the relation between subproblems, and then construct the optimal sub-problem.

Suppose we construct the optimal sub-problem from the first snapshot to the last one. For a merged snapshot \( T_{i_1,i} \), its time point is known, and this finish time is also the start time point of the remaining snapshots \( T_{i+1,n} \). Therefore, the start time point of \( T_{i+1,n} \) is also known. Since the topology of a snapshot is only related to its start time, the topology variation between \( T_{i_1,i} \) and \( T_{i+1,n} \) is known. The value of cost is determined because the cost in network topology variation from the merged snapshots to remaining snapshots. If we remove the merged snapshots \( T_{i_1,i} \), the cost will not matter to recursively solve the remaining problem \( T_{i+1,n} \). Hence, the relation between merged snapshots and remaining snapshots is destroyed. Sub-problems become independent, and the optimal sub-problem is constructed.

Suppose the first subset consisting of snapshots \( t_1,t_2,\ldots,t_l \) is optimum, they can be merged into a snapshot \( T_{i_1,i} \). The optimum subproblem \( T_{i+1,n} \) is denoted as \( \text{OPT}(i+1) \). Then, we get optimum value of the first subset.

\[
\text{OPT}(1) = e_{t_1,i} + w_c + C_{i_1,i+1} + \text{OPT}(i + 1)
\]

Because the first subset \( T_{i_1,i} \) and sub-problems \( T_{i+1,n} \) are independent, we can remove the first subset and use the same strategy for the sub-problem \( T_{i+1,n} \), denoted as \( \text{OPT}(i+1) \). Then, we can get \( \text{OPT}(i + 1) \) when we determine a \( t_k \) to produce a merged snapshot \( t_{i+1,...,t_k} \).

\[
\text{OPT}(i + 1) = \min_{i+1 \leq k \leq n} (e_{t_{i+1,k}} + w_c + C_{i_1,k+1} + \text{OPT}(k + 1))
\]

The algorithm is shown in Algorithm 1, which computes the optimal sub-problems from \( n \) to 1.

Analysis Algorithm. The algorithm complexity consists of computing the error and cost, and merging the snapshot.

For a known satellite network, it has a fixed number of satellites and ISLs. Thus, the running time of computing the error and cost of each pair \((i,j)\) is only related to the difference of \( j \) and \( i \), and the complexity is \( O(n) \). Since there are \( O(n^2) \) pairs \((i,j)\), the total running time is \( O(n^3) \). Furthermore, we can improve the algorithm in running time by limiting a difference between \( i \) and \( j \). If we set the difference to a constant value, the total running time of computing the error and cost will be decreased to \( O(n) \).

The algorithm has \( n \) iterations from \( n \) to 1, and the algorithm takes time of \( O(n) \) in each iteration. Thus, if the precomputed error and cost have been determined, the running time of our algorithm is \( O(n^2) \).

5 ANALYSIS ON ROUTING STABILITY

Since the topology of space Internet is continuously dynamic, the routing of space Internet is still in a state of instability. But this routing instability is different from that of ground network. In space network, the occurrence of instability can be considered as a discrete instantaneous event. Because the routing can be updated immediately once the topology varies.

Based on the cause of network topology variation, the occurrence of instability can be classified into two types, namely, one caused by the network connectivity variation and other caused by link metric variation.

5.1 Impact of Network Connectivity Variation

In order to reflect the impact of network connectivity variation, the concept of the snapshot based on the network connectivity is applied to modeling the network topology. With this concept, a new snapshot is created when some ISLs reconnect or disconnect. And when a new snapshot is created, the corresponding routing table will be updated.

From the experiment, we can get that about 1800 paths between two end satellites will be changed when some ISLs reconnect or disconnect. That accounts for about 41% of the total paths (the total is 66*66 = 4356). And about 25% of the total paths will be changed when some ISLs disconnect. In each update, so many changed paths will push the network into a chaotic state. Worse still, the occurrence of routing updates is very frequent, about once per 136.8s.

5.2 Impact of Link Metric Variation

We take an example with two orbits in a polar region to analyze the impact of link metric variation, as shown in Fig.3. And the ISL from satellite \( i \) to \( j \) is denoted as \((i,j)\).

For routing between two satellites in adjacent orbits, the shortest inter-orbit ISL will be chosen to adjacent orbit from the current orbit. As shown in Fig.3a, the routing from satellite S1 to T6 will

Algorithm 1 Dynamic Programming Algorithm

1: function SMA(n)
2:   Array OPT[1...n + 1]
3:   Set OPT[n + 1] = 0
4:   Compute all pairs error \( e_{i_1,j} \) and cost \( C_{i_1,j} \)
5:   for \( i = n, n - 1, \ldots, 2, 1 \) do
6:      \[ \text{OPT}[i] = \min_{i \leq k \leq n} (e_{i_1,k} + w_c + C_{i_1,k+1} + \text{OPT}[k + 1]) \]
7:   end for
8: end function
choose the inter-orbit ISL (S5, T5). Since all intra-orbit ISLs have the identical metric, the total sum of metrics of all chosen intra-orbit ISLs will be a constant no matter which inter-orbit ISL is chosen from ISLs (S1, T1), (S2, T2), ... Thus, the routing only relies on the candidate inter-orbit ISLs. The shortest ISL (S5, T5) is then chosen.

We explain the oscillation in the polar region as follows:

i. In Fig.3a, the newly reconnecting ISL (S5, T5) is chosen by the routing from S1 to T6.

ii. After 85s, (S3, T3) becomes smaller than (S5, T5) due to the satellite moving, shown in Fig.3b. Then the routing will switch to (S3, T3) from (S5, T5).

iii. Unfortunately, (S3, T3) is a nearly disconnecting ISL. When the time is 162s, this ISL will be dropped (shown in Fig.3c). The routing thus switches back to (S5, T5).

iv. In Fig.3d, (S2, T2) becomes smaller than (S5, T5) at 359s. The routing naturally switches to (S2, T2).

v. In Fig.3e, (S4, T4) reconnects at 548s. Since the newly reconnecting ISL (S4, T4) has the smallest metric, the routing thus switches to (S4, T4). Meanwhile, a new period will begin.

From the above analysis, we know that the selected routing is frequently changed, about once per 137s. For many users adopting this routing, they will suffer from the very poor performance, such as delay jitter, loss packets.

Unfortunately, the oscillation will always exist in the polar region. Because all satellites simultaneously move in their own orbits. When a nearly disconnecting inter-orbit ISL disconnects, a new ISL will become the nearly disconnecting ISL. And a newly reconnecting inter-orbit ISL will be created once an inter-orbit reconnects. Along with the link disconnection/reconnection, the metrics of dynamic ISLs continuously vary. The polar oscillation continuously occurs, and meanwhile those ISLs where polar oscillation occurs constantly change.

Extremely, because the paths between two satellites at the both sides of seam have to go through the polar region, there are about 1260 paths passing the newly reconnecting inter-orbit ISLs and 630 paths passing the nearly disconnecting ones in a polar region. They respectively account for about 30% and about 15% of the total paths (4356). Since the satellite constellation has two polar regions, the number of paths and times of switches will be double!

That means so many paths frequently vary along with the variations of metric and network connectivities, causing polar oscillations and putting great pressure on the network stability. Especially, when many paths switch forth and back on some overloaded ISLs, the network performance will suffer from catastrophic damage, such as severe packet loss.

6 ROUTING SCHEME

Designing a stable routing scheme for polar oscillation is challenging because of its time-varying property. Not only the network connectivity and link metric that cause polar oscillation is varying, but also the overloaded ISLs where polar oscillation occurs constantly vary with the satellite movement. For locating the ISL where polar oscillation occurs, we define the life-time of ISL, and build a stable routing scheme:

1) Considering the link-time of some dynamic ISLs into their metrics, to weaken the influence of ISLs disconnect/reconnect and eliminate the relatively variation of their metrics.

2) Based on the link metric function and topology of space network, we take use of a current routing algorithm–Dijkstra algorithm to decrease the number of paths sharing the overloaded ISLs, and to avoid the corresponding paths oscillating on those ISLs.

6.1 Link Metric

First, we define a link life-time for every inter-orbit ISL. The link life-time changes as the satellite moves. The newly reconnecting inter-orbit ISL has a largest life-time, while the nearly disconnecting inter-orbit ISL has a smallest life-time. However, when the ISL moves into the polar region, its life-time becomes zero.

When a link reconnects, its life-time will change from zero to the largest. While the link disconnects, its life-time will change from the smallest to zero. Meanwhile, the variation of link metrics can be mapped to the variation of link life-time due to the fact that all satellites move at a certain angular velocity. Hence, the variations of inter-orbit ISLs connectivity and metrics can be formulated by the life-time of link. According to the cause of polar oscillation, the ISL with a largest/smallest life-time also is the ISL where polar oscillation occurs.

In order to weaken the influence of ISLs disconnect/reconnect and eliminate the relatively variation of ISLs metrics, we consider the life-time of those ISLs into their metric and formulate link metric function as follows.

\[
MF = \begin{cases} 
\frac{\zeta}{\text{life-time}} & \text{if and only if the ISL with a largest/smallest life-time} \\
\frac{\text{propagation delay}}{\text{life-time}} & \text{otherwise}
\end{cases}
\]

For the inter-orbit ISLs with a largest/smallest life-time, their metrics are set to a constant value \(\zeta\). For other ISLs, their metrics are computed by their own propagation delays. The metric \(\zeta\) is set to a value that is slightly smaller than the delay of inter-orbit ISL when it just becomes the nearly disconnecting inter-orbit ISL. And the value of \(\zeta\) is also smaller than the delay of intra-orbit ISL.

Fig.4 shows the comparison between original and optimized topology. Metrics of link (T5, S5) and (T3, S3) are the same. And other part of the network topology remains relatively unchanged, due to the fact that metric of (T3, S3) is still smaller than that of (T2, S2), and metric of (T5, S5) is still smaller than that of (T6, S6). Thus,
or (S5, T5). It can be proved by the greedy poverty of ISLs from a certain path, the section between these two points reconnects, it will immediately take the role of (S5, T5) and of Dijkstra: the best path from S3 to T5 is the path passing through (S4, T4) reconnects, it will immediately take the role of (S5, T5) and of Dijkstra algorithm [21]. When we pick out any two points of satellite S1 to T6 and from S6 to T1. In Fig. 4a, with the original topology, both two pairs will go across (S5, T5), because the metric of (S5, T5) is smaller than that of (S3, T3). After a short time, all of them will go across (S3, T3), because the metric of (S3, T3) become smaller than that of (S5, T5). However, in Fig. 4b with optimized topology, the best path from S1 to T6 will go across (S3, T3), while the best path from S6 to T1 will go across (S5, T5).

**Proof.** In Fig. 4b, the best path from S1 to T6 can be represented by the best path from S3 to T5, according to the optimality principle of Dijkstra algorithm [21]. When we pick out any two points (satellites) from a certain path, the section between these two points is a part of the original path.

Suppose we pick out the two points – S3, T5 that has two equal-cost paths. The best path from S3 to T5 is the path passing through (S3, T3) rather than (S5, T5). It can be proved by the greedy poverty of Dijkstra:

i. The cost from point S3 to T5 is constant whether the best path passes through point S5 or T4. As the metric of ISL (T4, T5) is smaller than that of (S5, T5), the cost from S3 to T4 is smaller than that to S5.

ii. According to the greedy property of Dijkstra [21], the algorithm will firstly select the point T4 to compute the cost of T5, then the minimal cost of T5 will be achieved.

iii. In the next step, the algorithm will select S5 to compute the cost of T5. In this case, the cost of the path passing through S5 is not better than but equal to the current cost of T5. The algorithm will not update the cost of T5, and the father point of T5 will also remain unchanged. Thus, the best path from S3 to T5 still passes through (S3, T3) and point T4.

The path from S1 to T6 will also go across (S3, T3). While the best path from S6 to T1 is across (S5, T5). Their best paths will not be changed until (S3, T3) disconnects or (S5, T5) moves out of this region. Compared with the routing of original topology, the number of paths sharing the inter-orbit ISL (S3, T3) or (S5, T5) is decreased, and corresponding paths switching on those ISLs is avoided.

### 6.3 Discussion

In fact, the routing algorithm is not sensitive to the value of $\zeta$. For keeping the topology of overall network relatively unchanged, it should be set to a value that is slightly smaller than the delay of inter-orbit ISL when it becomes the nearly inter-orbit ISL.

Besides, other shortest path algorithms may not work in our scheme, such as the Floyd-Warshall algorithm. That is because this algorithm selects the best path from some equal-cost paths by satellite-ID [10]. For example, let the satellite-ID as follows: $T3 < S3 < T4 < S4 < T5 < T6$, the routing from T3 to S5 and from T5 to S3 will simultaneously go through (T3, S3). Those inter-orbit ISLs will still suffer from the overloaded routing. When the connectivities of those ISLs change, many paths will be changed and the network performance will be damaged. Moreover, the satellite-ID is constantly varying at the polar region due to the satellite moving. The routing will thus suffer from the instability of satellite ID unless we design a stable numbering scheme for satellites, which is not our concern in this paper.

### 7 Experiment

In this section, we assess the performance of our method in comparison with other two concepts of modeling the network topology, namely DT-DVTR and PLSR. In order to avoid some links unused or broken down between adjacent routing updates, we modified the concept of DT-DVTR. The routing update of DT-DVTR will not only follow its own concept, but also occurs once the topology changes. The interval time of DT-DVTR is set to 60s according to [28]. In the concept of PLSR, the routing update occurs only when the topology changes. In our method, the divided snapshot is created like the modified DT-DVTR, but the interval time is set to 30s. They all apply the Dijkstra algorithm to calculate the routing table. With the network topology shown in Figure 1 and TABLE 1, we conduct experiments on NS2.

#### 7.1 Effect of Parameters

Let us analyze the effect of three weights in our model, namely $w_m$, $w_m$, and $w_c$, which respective are the weights of network connectivity variation, link metric variation, and the cost of routing update. First, we set $w_c$ to one, and change the other two. In order
to avoid conflicts, we adopt the control variate method. When one of remaining weights is increased step by step, the other is set to zero. When a weight becomes larger, the corresponding indicator becomes more important.

In Fig.5, with the weight increasing, the number of routing updates will achieve a steady value. The steady value in Fig.5a is equal to the number of network connectivity variations over a system period. And the steady value in Fig.5b is equal to the steady value when we set the two weights big enough values. That steady value is also the minimum of snapshots to reflecting the topology variation best. The minimum is 67, and it is about one-third of total divided snapshots (222).

### 7.2 Analysis of Routing Stability

In ground Internet, there are three primary indicators of routing stability: network convergence time, additional resource overhead (memory, CPU, etc.) and the number of route flaps [4, 22]. The use of predictable characteristics of topology can eliminate the routing convergence time, but introduce the number of routing updates. Thus, we define three indicators for the space Internet stability: (i) number of routing updates over a system period; (ii) number of changed paths; (iii) number of affected satellites. The first two indicate the variation of routing, while the last one indicates the resource overhead for dealing with routing update.

Fig.6 shows that our method can significantly decrease the number of changed paths and affected satellites in comparison with others. And the reduced ratios are almost the same, which are about 50% of PLSR, and about 32% of DT-DVTR. Our method achieves an average of 761.7 changed paths and 22.7 affected satellites for each routing update. The result of PLSR is worst, which incurs an average of 1425 changed paths and 45 affected satellites. They respectively account for 41.3% and 72% of the total. The modified DT-DVTR has a slightly smaller number of changed paths and affected satellites than that of PLSR.

On the other hand, our method requires 67 times of routing updates, which is less than DT-DVTR by 22 and more than PLSR by 19. However, in our method, the total number of changed paths and affected satellites are smaller than others. The reduced ratios of changed paths and affected satellites are about 20% of PLSR, and about 50% of DT-DVTR.

Fig.7 shows that our method achieves the least number of total changed paths than others no matter how large of the boundary.

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**Table 2: Simulation parameters**

| Parameter          | Value                  |
|--------------------|------------------------|
| Link capacity      | 12 Mb/s                |
| Number of users    | 100                    |
| Packet length      | 1000 B                 |
| Transmission rate  | 1.0 \(-\) 1.6 Mb/s     |
| Simulation duration| 900 s                  |

---

**Figure 5: Effect of weights.**

**Figure 6: Comparison of stability among three models.**

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**Figure 7: Changed paths over a system period.**

**Figure 8: Affected satellites over a system period.**

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**7.3 Performance of Network**

In this subsection, we discuss the performance of network. The parameters in simulation are shown in TABLE 2. As the space network serves all people no matter where they locate and when they access, we pick out 100 users who are randomly distributed in global, the communications of which is random.

We adopt some important factors to identify the network performance of different methods, namely, the number of packet loss, maximum link utilization, and the end-to-end delay [1, 14]. The utilization of a link is defined as the ratio of the load over its capacity during a certain time. And the max-utilization is maximum utilization among all links.

Fig.8 shows that our method can drastically decrease the loss packets rate regardless of the link load. Because the use of Dijkstra’s greedy property in our scene can drastically decrease the number of...
paths sharing the overloaded ISLs. However, the Dijkstra algorithm in other two methods can’t achieve this contribution.

For fairness, when we analyze the maximum utilization and end-to-end delay of three methods, the transmission rate of user is set to 1Mb/s where all methods don’t loss packets. The end-to-end delay is defined to be the delay between two access satellites, avoiding the effect of handover between users and access satellite. The satellites are accessed by two users that are randomly picked out. They are respectively located at (61.20N, 180E) and (77.4S, 75.6W), and the shortest path between them passes through the north polar region.

Fig.9 shows that the variation of end-to-end delay in our methods is smoothest. During a short time, the delay of our method is slightly larger than other two methods, but the average delay of all methods are almost the same, about 82ms. Meanwhile, the standard deviation of delay in our method is the smallest, about 1.3ms, which is about 12% smaller than that of PLSR and about 8.5% smaller than that of DT-DVTR. Thus, the variation of delay in our method is smoothest.

We note that Fig.9 has three regions where the delay is very large, which are caused by the handover between access satellite and destination user. The packets arriving at the current satellite is rerouted to the new access satellite, as the user accesses a new satellite.

In Fig.10, with the same load, the maximum utilization of our method is the smallest all the time. The maximum utilization of other two methods is almost the same. Compared with other two methods, the peak value of the maximum utilization in our method is reduced by about 18%, and the average maximum utilization is decreased by about 20%. Meanwhile, the variation of maximum utilization in our method is smoothest.

8 RELATED WORK

For traditional Internet with static topology, the routing protocols (like OSPF, RIP) are mostly based on constantly refreshed network state or routing information to get the real network topology. However, for the space Internet with continuously dynamic topology and limited resource, these protocols will incur heavy overhead and severely damage network performance [2]. For dynamic networks (eg. ad-hoc network), although many routing protocols have been presented, these methods mostly aimed to the unpredictable or not completely predictable dynamic topology [6]. These protocols will also suffer from control packet overhead or reduced throughput similar to the conventional routing protocols. Therefore, these topology models and routing protocols will be inadequate to this predictable dynamic network [13].

On the other hand, some researchers supposed that the construction and management of ISLs are so difficult that space networks do not provide the real time transmission path, and applied DTN (delay/disruption tolerant network) topology models and routing to space network [7, 8]. With the utilize of predict and geometric characteristics of space network, the construction and management of ISL will become practicable. Therefore, many topology methods and routing schemes specific to the predictable dynamic network have been presented [13, 15, 28, 29].

8.1 Topology Modeling

Up to date, there are two methods modeling the continuously dynamic topology based on its predictability. One is to divide the dynamic topology over a system period only based on a fixed time interval (e.g. 60s) [28, 29], while the other one is based on the concept where ISL disconnect/reconnect-only induced topology variations [13, 15]. They all just adopted a simple method to divide the continuously dynamic topology, and didn’t model the dynamics of space network accurately. Moreover, all of them didn’t realize that the continuously dynamic topology can keep relatively unchanged during a period of time, and the topology during this duration should not be divided.

Besides, the virtual node (VN) concept base on the geometric characteristic of the network topology has been proposed to hide the dynamic characteristics of network [11, 23]. However, this approach will push high computational complexity in space devices, and suffers from the outage phenomenon [2, 17]. The topology model also can be considered as a special case of DT-DVTR whose the time interval is set as the value of system period divided by the number of satellites per orbit.

8.2 Routing Schemes

With the development of promising network technology specific to space network, many routing schemes have been proposed. In the satellite network based on ATM technology, [28, 29] proposed a space-time routing framework based on the topology model of DV-DTTR. However, the success of ground Internet will make it difficult to integrate with these networks. With the development of space network, the building of space Internet become a trend, and most recent presented routing schemes are based on IP technology. With the utilization of geometric characteristic of network topology, some routing schemes based on the VN model [11], position information [17] and multi-layered constellation are proposed. Without the use of predictable characteristic, those proposals will incur some overhead for space network. [13] proposed a routing
framework joining the predictive of dynamic topology and Link State Protocols (eg. OSPF). However, all of them mainly proposed a routing framework, and have not considered the routing stability or routing imbalance in the predictable dynamic network.

Since the issue of routing stability is very important for network infrastructure, it has obtained many attentions on traditional Internet [4, 22]. Meanwhile, this issue has yet gotten some attentions along with the coming of space of Internet. Some authors including the Aerospace corporation have experimentally analyzed the routing convergence of traditional routing protocols (eg. BGP) in space network [5, 16, 18]. But they did not provide any proposals or realize the issue of polar oscillation.

As the routers of satellite nodes are extremely far away from each other, most current routing schemes take the propagation delay as their link metrics [11, 20]. And the inter-orbit ISLs close to the polar region have a shorter delay, which draws most traffic into the polar region. For LEO Celestri constellation without the variation of network connectivity, the authors [24, 26] proposed two methods of alternating deflecting the routing in the source node and alternating deflecting the routing in all nodes. These methods could achieve load-balance well, but they drove most packets not to be delivered along the best routing. In term of polar LEO constellation with the polar oscillation, these methods even aggravate the instability of network.

9 CONCLUSION

For dividing continuously dynamic topology into the least number of static topologies with reflecting the topology dynamics correctly, we build a topology model based on Divide-and-Merge methodology. Then we design a dynamic programming algorithm to solve that model and determine the timing of routing update and the topology to be used. Furthermore, we deeply analyze the issue of polar oscillation and provide a novel routing scheme. In this scheme, the life-time of some dynamic links is considered into their metrics. Then we use of Dijkstra’s greedy property to release some paths from the dynamic links, and to avoid some paths switching back and forth on these links.

Our experimental results show that our methods can make the network more stability and achieve a better network performance.

Besides, our topology model and routing scheme are simple but effective, which can be the basic element for many routing schemes. The topology model can be easily adapted to other predictably dynamic networks. Meanwhile, the routing scheme mainly relies on the current routing technology, which can be a basis for many Internet technologies to be implemented on the space network.

In future, we will analyze the influence of the seam on routing stability, which has not been implemented by the current LEO constellation. And we will take the rare accident events into our routing scheme, such as satellite failure, link interruption.

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