GALOR: GLOBAL VIEW ASSISTED LOCALIZED FINE-GRAINED ROUTING FOR LEO SATELLITE NETWORKS

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Abstract – *Low Earth Orbit (LEO) satellite networks have been expected to provide global coverage for Internet services with immediacy requirements. The dynamics of an LEO satellite network topology induce the challenges of achieving efficient content retrieval. This article takes an initial step toward achieving efficient content retrieval in LEO satellite networks from the routing perspective. We start with investigating the topology characteristics of LEO satellite networks in terms of the deterministic neighbor relation and the intermittent inter-satellite links. We then propose a Global view Assisted Localized fine-grained Routing (GALOR), which is an information-centric routing mechanism customized to LEO satellite networks. Specifically, GALOR disseminates the link state within a predefined range instead of the entire constellation, incurring less convergence time and control overhead. Therefore, GALOR can calculate the routing table (to guide interest forwarding) based on the local link state and the global neighbor relations. Moreover, GALOR improves the forwarding method of the information-centric routing by reconstructing a failed Pending Interest Table (PIT) entries in response to occasional link failures. Our packet-level experiments show that GALOR outperforms state-of-the-art mechanisms (up to 103.4%) in terms of average packet delivery ratio in content-sharing.*

Keywords – Content retrieval, LEO satellite networks, named-data networking, routing protocol

1. INTRODUCTION

1.1 Background and motivations

Over the past decades, we have witnessed the proliferation of many Low Earth Orbit (LEO) constellations (e.g., Iridium [1], OneWeb [2], and Starlink [3]) deployed by cutting edge companies and academic institutions. The LEO constellations equipped with Inter-Satellite Links (ISLs) have the potential to provide high-speed broadband Internet services for terrestrial users around the world [4, 5], e.g., video streaming and remote sensing. However, achieving efficient content retrieval via the LEO constellation is challenging due to a dynamic topology [6]. The *inter-orbit* ISL between two satellites in adjacent orbits will be switched off within the polar zone due to the high-speed relative velocity [7, 8]. In addition, occasional ISL failures (due to antenna-pointing errors and antenna tracking limitations) also affect the topology of the satellite network. The topology changes occur more frequently when the constellation scales up, deteriorating the content delivery performance [9]. To achieve efficient data delivery in LEO satellite networks, it is crucial to adopt an appropriate networking architecture and routing mechanism that can accommodate the topology characteristics.

IP networking and Named-Data Networking (NDN) are typical routing architectures used in terrestrial Internet. However, either the classic IP-based or the NDN-based routing architecture cannot achieve this goal in an LEO satellite network. Specifically,

- IP networking is host-centric and designed based on IP addresses assigned to hosts (or interfaces). The routing table in IP networks records the reachability of all the hosts (i.e., the destination IP address). This requires that IP-based routing schemes [10, 11, 12] rapidly propagate the network topology change within the entire network to ensure global reachability. Thus, it can accommodate the intermittent ISLs better under the strong topology dynamics. But it will inevitably cause redundant content delivery for the content-sharing scenario [13].

- NDN is information-centric and designed based on the name assigned to content (or content chunk). It uses Interest/data packets to disseminate routing updates and deliver requested content in a pulling manner.[1]). The information-centric philosophy naturally enables in-network content caching and interest aggregation, which can reduce content retrieval delay and redundant data delivery (compared to IP networks) [14]. Nevertheless, NDN-based routing (i.e., Named-data Link State Routing protocol (NLSR) [15]) still suffers from excessively frequent topology changes caused by satellite mobility [16, 17]. Moreover, it cannot accommodate the intermittent ISLs

[1]NDN is one of the prominent Information-Centric Networking (ICN) architectures.

as soon as possible, leading to poor routing performance under the point-to-point content delivery scenario [9].

Motivation: According to the above description, there is no universal routing mechanism perfectly adapting to any networks. Information-centric routing architecture is stateful and can achieve efficient content delivery for content-sharing compared to IP-based [18]. However, information-centric routing cannot accommodate the intermittent ISLs, leading to poor performance under point-to-point delivery scenarios [9]. Moreover, host-centric routing architecture is stateless and thus can accommodate the intermittent ISLs better than information-centric routing [19]. Nevertheless, host-centric routing will inevitably cause redundant content delivery and thus cannot accommodate the content-sharing delivery scenario. Furthermore, the mobility nature of the LEO satellite network may cause frequent short-term ISL connectivity changes (due to antenna tracking errors) [20]. Thus, ISL state change incurs frequent global routing updates [7, 10, 12, 21].

Overall, it is clear that information-centric routing architecture has the potential to achieve efficient content sharing. This motivates us to explore whether the global awareness of the real-time ISL state is necessary, i.e., synchronize the ISL state change within a limited range instead of the entire constellation. Indeed, the intrinsic reason for such an ISL state synchronization strategy is that an ISL state change has little effect on the satellites far from this ISL in an LEO constellation [7, 21]. Thus, one could definitely improve the existing information-centric routing mechanisms (i.e., NLSR) based on the topology characteristics of LEO networks to achieve efficient content sharing. This leads to our key question in this article:

Question 1 *How can we improve the existing routing mechanism (i.e., NLSR) according to the topology characteristics in LEO satellite networks?*

To address the above question, a promising routing mechanism is to maintain a limited range of real-time ISL states by synchronizing the ISL state change within the range, yielding less control overhead. Moreover, we also improve the forwarding method of the information-centric routing by reconstructing failed Pending Interest Table (PIT) entries in response to occasional link failures to achieve efficient content retrieval.

1.2 Main results and contributions

This article focuses on achieving efficient content delivery in LEO satellite networks by leveraging the determined neighbor relation. Specifically, we will first take an initial step towards customizing an NDN-based routing mechanism to accommodate the topology characteristics in LEO satellite networks. We then adopt the NDN-based content retrieval pattern and design a proactive interest retransmission to reconstruct the destroyed content delivery path to achieve efficient content delivery in satellite networks. Our main results and key contributions are summarized as follows:

- *Design an NDN-based link-state routing for satellite networks:* We present the design of a Global view Assisted Localized fine-grained Routing (GALOR), which is an NDN-based routing mechanism customized to LEO satellite networks. Specifically, GALOR disseminates ISL state within a predefined range by controlling the propagation radius, incurring less control overhead. Moreover, GALOR calculates the routing table (to guide interest forwarding) based on local ISL states and the global neighbor relation.

- *Propose a proactive interest retransmission mechanism:* To deal with ISL failure, GALOR improves NDN-based content retrieval by reconstructing failed Pending Interest Table (PIT) entries in response to the occasional ISL failures to deliver reliable content.

- *Performance evaluation:* We explore the performance of GALOR under the Iridium constellation based on the packet-level experiments. The results show that GALOR outperforms IP-based routing and NDN-based routing up to 103.4% and 9.33% in terms of packet delivery ratio, respectively.

The rest of this article is organized as follows. Section 2 reviews the related studies on information-centric satellite network routing. Section 3 introduces the features of satellite networks. Section 4 presents the key idea of GALOR. Section 5 elaborates the design detail of GALOR. Section 6 evaluates the performance of GALOR. Section 7 concludes this paper.

2. RELATED WORK

We now review the related literature to our study. These include applying ICN to LEO satellite networks and ICN-based satellite network routing.

2.1 Applying ICN to LEO satellite networks

ICN adopts a receiver-driven model, which is content-centric [14]. The named content can be cached in the network and reused for subsequent requests, enabling efficient content retrieval. Therefore, there is increasing interest in applying ICN to LEO satellite networks [22, 23, 24]. Most of them aim to explore the possible advantages of applying the ICN to satellite networks. For instance, Detti *et al.* in [23] propose an ICN-based satellite architecture in that users get Internet access through a GEO satellite to demonstrate the advantages of applying ICN to satellite networks. The experiment results show that ICN can reduce the downstream traffic (up to 46%), i.e., from satellites to customers. Ververidis *et al.* in [25] integrate the ICN feature with a satellite network to explore the potential gains in terms of multipath/multisource transfer, in-network caching, and traffic management. The experiment results reveal that the time to download the cached files drops up to 71.8%. Thus, the in-network caching reduces the usage of the ISL. Moreover, several studies attempted to apply ICN to satellite-assisted emergency communication (e.g., [26]) and multi-link backhauling scenarios (e.g., [27]). For example, Cola *et al.* in [26] explore the use of ICN architecture in emergency communication and find that ICN caching can reduce the message delivery delay and overall traffic load. Furthermore, Cola *et al.* in [27] propose an extension of the PURSUIT architecture (i.e., one of the prominent ICN architectures) for multi-link backhauling in highly mobile satellite network environments. The result shows that the capacity saving of PURSUIT gains up to 45% over IP due to the inherent in-network caching ability of PURSUIT. However, the studies above only consider the single-satellite scenario. Therefore, exploring their content delivery performance in multi-scale LEO satellite networks is necessary.

2.2 ICN-based routing for satellite networks

Note that ICN shifts the communication model from host-centric to content-centric [14]. This requires the role of routing in ICN to advertise the content names and compute the content routing table for the interest packet forwarding. Thus, there are a few studies (e.g., [28, 24, 29, 20]) that focus on ICN-based routing in satellite networks. Liu *et al.* in [28] introduce a VN-based matrix algorithm to calculate a routing table for guiding interest forwarding in satellite networks. Yan *et al.* in [20] present a Logic Path Identified Hierarchical (LPIH) routing mechanism to harness the advantage of host-centric routing and the benefit of information-centric routing. The experiment results show that LPIH reduces the control overhead up to 64.37% and improves the packet delivery ratio compared to ICN. Moreover, several studies focus on the consumer mobility issue in satellite networks[16, 17]. For example, Liang *et al.* in [16] deal with satellite handover by designing a consumer-initiated interest retransmission scheme, achieving higher data retrieval efficiency up to 90.9%. Xia *et al.* in [17] reduce redundant content delivery by introducing a shim layer in the communication model, enabling data recovery from the previously connected satellite. However, they overlook how to manage the strong dynamic satellite network and do not consider the disabled PIT entry due to the occasional ISL failure. This article will address these issues by relying on the satellite network topology characteristic and interest retransmission by intermediate satellites.

3. SYSTEM MODEL AND TOPOLOGY CHARACTERISTICS

In this section, we first introduce the satellite network model in Section 3.1. Then, we introduce the topology characteristics of LEO satellite networks in Section 3.2.

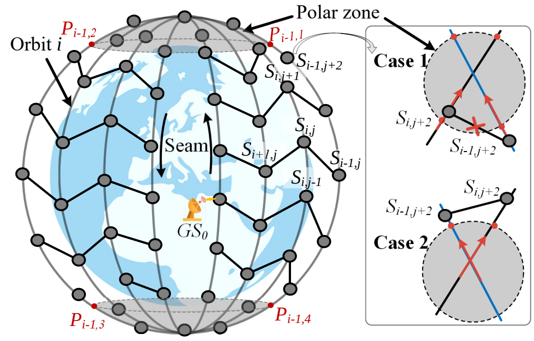


Fig. 1 – Satellite network model.

3.1 Satellite network model

We consider a polar satellite constellation (e.g., Iridium and OneWeb). As shown in Fig. 1, an LEO satellite network consists of N orbital planes and M satellites on each plane. We let $\{S_{i,1}, S_{i,2}, ..., S_{i,M}\}$ denote the M satellites on the i-th orbital plane. The orbital inclination of the polar constellation is around ninety degrees (e.g., 87.6 degrees for OneWeb). Moreover, all the satellites orbit at the same altitude, and the satellites in the same orbital plane are uniformly distributed on the orbit. Thus, the angular distance among two adjacent satellites in the same orbital plane is $\omega = 2\pi/M$. The phase offset between two neighboring satellites in adjacent orbital planes is $\Delta\omega = \pi/M$. These imply that the neighbor nodes of any satellite can be determined based on their relative positions in a constellation (to be elaborated in Section 3.2).

Each satellite connects to its four neighbor satellites via Inter-Satellite Links (ISLs) relying on Ka/Ku-band (e.g., Iridium) or laser (e.g., Starlink). For instance, as shown in Fig. 1, the satellite $S_{i,j}$ has four neighbors $\{S_{i+1,j}, S_{i,j+1}, S_{i+1,j}, S_{i,j-1}\}$. Particularly, there is a *seam* between the first and last orbit plane since the satellites move in opposite directions, as illustrated in Fig. 1. The *inter-orbit* ISLs between the first and last orbit plane will be switched off. Hence, the satellites in the first and last orbit plane have three neighbors.

3.2 Topology characteristics

The LEO satellite networks exhibit two typical characteristics, e.g., deterministic neighbor relationship and intermittent ISLs.

3.2.1 Deterministic neighbor relationship

There is a deterministic neighbor relationship among the adjacent satellites in an LEO constellation. Specifically, the orbital period of LEO satellites at the same altitude is the same. The relative position of adjacent satellites remains fixed no matter how the satellite's orbit (even if there is an orbit crossing). As one can imagine, the neighbor relationship between any two adjacent satellites is predefined and deterministic in an LEO satellite network, even if path stretch and path contraction occur, derived from the satellite's movement. For instance, as shown in Fig. 1, the neighbor relation of $S_{i,j}$ and $S_{i+1,j}$, $S_{i,j}$ and $S_{i,j+1}$, $S_{i,j}$ and $S_{i-1,j}$, $S_{i,j}$ and $S_{i,j-1}$ are determined based on their relative positions in the orbit. Note that the satellite network topology may not be stable since the ISLs are intermittent. This feature does not exist in other mobile ad hoc networks or terrestrial Internet. One could leverage this feature to reduce the control overhead of ISL state synchronization.

3.2.2 Intermittent ISLs

In a LEO satellite network, there are two types of ISLs, i.e., intra-orbit ISLs and inter-orbit ISLs. The high mobility nature of LEO satellites incurred frequent ISL short-term churn, i.e., the ISL fails and recovers. Particularly, the mobility of LEO satellites has a small impact on the intra-orbit ISL but will significantly affect the connectivity of inter-orbit ISL [7]. Specifically, the relative angular speed between two adjacent satellites in adjacent orbital planes will increase when satellites move toward the polar zone. Such a relative movement will increase the challenge for antenna alignment (especially for laser ISLs). The inter-orbit ISL will temporally fail if the antennas of the corresponding satellites are misaligned, which causes topology changes. This phenomenon is severe when satellites are in the polar zone. In practice, the inter-plane ISLs will be switched off (or switched on, respectively) when the corresponding satellites enter (or leave, respectively) the polar zone, as illustrated by **Case 1** (or **Case 2**) in Fig. 1. As one can imagine, the topology dynamics caused by the intermittent ISLs will increase as the constellation scales up. This feature renders efficient data retrieval in large-scale LEO constellations more challenging.

4. GLOBAL VIEW ASSISTED LOCALIZED FINE-GRAINED ROUTING MECHANISM

This section introduces our proposed GALOR mechanism. We first provide an overview of the GALOR mechanism by introducing the key idea and an illustrative example. We then introduce the naming space of the GALOR mechanism.

4.1 Key idea of GALOR mechanism

4.1.1 Routing rationale of GALOR

Recall that the relative phase among the adjacent satellites is fixed in LEO satellite networks, thus the neighbor relation is deterministic. Moreover, an ISL state change has little effect on the routing of satellites far from this ISL (e.g., [21]). For example, as shown in Fig. 2, if the ISL between satellites $S_{3,2}$ and $S_{4,2}$) failure occurs and the failed ISL will recover after a short period, the frequent ISL short-term churn brings frequent routing table updates with little effect in the packet forward in satellite $S_{1,4}$. This observation implies that it is not necessary to disseminate the ISL state changes within the entire constellation. However, both classic IP-based routing, i.e., OSPF [30], Area-based Satellite Routing (ASER)[21], and ICN-based routing (i.e., NLSR) disseminate the ISL state changes within the entire constellation, which actually causes great control overhead and raises the routing convergence time. Therefore, our proposed GALOR mechanism tends to leverage the localized fine-grained ISL state and the deterministic neighbor relationship from the following two aspects.

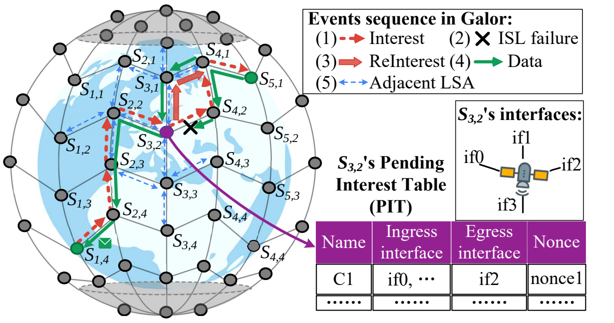


Fig. 2 – Illustration of content retrieval in GALOR. "intf" stands for a physical interface in the satellite.

- *Local dissemination of ISL state:* GALOR satellites periodically detect the connectivity of ISLs via the hello mechanism (like OSPF). Thus, GALOR satellites can maintain the ISL connectivity information between the satellites. Moreover, GALOR satellites only disseminate the ISL state changes within a few hops in LEO satellite networks. In this case, each GALOR satellite only maintains the real-time states of its nearby ISLs but does not know whether the other ISLs (far from it) function normally.
- *Global view of neighbour relation:* Each GALOR satellite will calculate the routing table (for interest forwarding) based on its local ISL states and the global neighbor relation. In this process, those ISLs far from this GALOR satellite are presumed to be working normally by default. Note that such a topology inaccuracy could be gradually mitigated during the forwarding process of the interest.

4.1.2 Proactive interest retransmission

In NDN, the ISL failure may destroy the content retrieving route recorded by the corresponding PIT entries since it adopts the stateful forwarding. This phenomenon becomes severe when the topology of LEO satellite networks frequently changes. Our proposed GALOR will overcome this drawback by resending the interest packets to reconstruct the destroyed content delivery path. To achieve this goal, the GALOR satellite records the interest packet's ingress and egress interfaces, as shown in Fig. 2. Therefore, if there is a PIT entry whose egress interface corresponds to the failed ISL, then the GALOR satellite will retransmit an interest packet associated with the content name of this PIT entry. The retransmitted interest may reach the provider or may be aggregated during the packet forwarding. In this case, the content delivery path could be quickly reconstructed in response to ISL failures. Fig. 2 shows an example of content retrieval under the GALOR mechanism. The red arrows represent the interest packet forwarding progress, and the blue arrows represent the forwarding progress of data packets.

4.2 An illustrative example

We demonstrate how GALOR works briefly with the help of Fig. 2. Specifically, a terrestrial user (covered by satellite $S_{1,4}$) requests the content C_1 provided by the provider (covered by $S_{5,1}$) via the satellite network. The process of content fetching under the GALOR mechanism is as follows (inherited from NDN).

- The red dash arrows represent the interest-forwarding path (e.g., $S_{1,4}$→$S_{2,4}$→...→$S_{5,1}$) for content C1 according to the GALOR routing table. Moreover, Fig. 2 takes the satellite $S_{3,2}$ as an example and shows its PIT. Note that the PIT entry associated with content C1 records the ingress interface if0 and the egress interface if2. Such a stateful forwarding scheme naturally supports interest aggregation. That is, if a satellite receives multiple interests for the same content within a certain period, it could only forward the first one to avoid redundant data delivery.
- After the interest packet reaches the provider (i.e., covered by satellite $S_{5,1}$), the ISL between satellites $S_{3,2}$ and $S_{4,2}$ fails (due to antenna-pointing errors). Hence, the content delivery path (i.e., the inverse path of red dash arrows) becomes invalid.
- Once the GALOR satellite $S_{3,2}$ detects the ISL failure, it updates its interest routing table and resends the interest packet (for content C1). The red solid arrows in Fig. 2 represent the forwarding path of the resent interest packet. Note that the retransmitted interest may reach the provider or may be aggregated during the packet forwarding, which is aggregated at satellite $S_{4,1}$. In this case, the content delivery path could be quickly reconstructed in response to ISL failures.
- The data packets will be delivered according to the reversed path recorded by the PIT entries, as shown by the green solid arrows in Fig. 2. In this example, the data packet could be successfully delivered to the satellite $S_{1,4}$. Nevertheless, some redundant transmissions may unavoidably be yielded.

From the above description, it is clear that the packet forwarding pattern of GALOR can reduce redundant packet delivery via interest aggregation and content in-network caching.
So far, we have introduced how GALOR works based on the example in Fig. 2. Next, let us move on and present the naming space of GALOR.

4.3 Design of naming space for GALOR

GALOR adopts a hierarchical scheme (as adopted in previous studies, e.g., NDN [14]) to denote the relationship between the key components in the LEO satellite network. Specifically, the naming space includes the Node Identifier (NID), ISL state acknowledgement message, and the content name.

4.3.1 Node identifier

In GALOR, we assign each satellite a globally unique Node Identifier (NID) instead of assigning an IP address to each interface. Specifically, the NID of a satellite is named according to the network it resides in, the orbital plane, as well as the number on the plane, i.e., $/\langle Network\rangle/\langle satellite\rangle$. For instance, a satellite in GALOR may be named $/LEOnetwork/S_{i,j}$. Particularly, we let $S_{i,j}$ denote the j-th satellite on the i-th orbit plane. In GALOR, NID will be used in interest routing.

4.3.2 Content name

Our proposed GALOR mechanism is information-centric and assigns each content a unique name, which follows a hierarchical structure (similar to NDN). To obtain a piece of content, the user (or content consumer) will request the desired content. If the request reaches the content provider or an intermediate node that has cached this content, then the corresponding content data will be delivered back to the user. In the example of Fig. 2, the terrestrial user covered by $S_{1,4}$ will request the content C_1 provided by the provider covered by $S_{5,1}$.

4.3.3 Network state advertisement message

As a link-state routing, GALOR uses two types of Link State Advertisements (LSAs) to disseminate the network state, including ISL state advertisement and the content reachability information. Accordingly, the name of an LSA can be denoted as $/\langle network\rangle/\langle satellite\rangle/\langle LSAtype\rangle/\langle version\rangle$. Note that the $version$ indicates the freshness of the LSA generated by the originating satellite. Specifically, in our design, we adopt a hello mechanism to detect ISL connectivity. When an ISL state change (i.e., ISL failure) is detected, it will initiate an ISL state advertisement (Adjacent LSA) to the adjacent satellites, which is denoted as $/LEOnetwork/S_{i,j}/AdjacencyLSA/01$. Moreover, we adopt a similar name format with an adjacent LSA to announce the content reachability, i.e., $/LEOnetwork/S_{i,j}/NameLSA/01$.

So far, we have introduced the key idea and naming space of GALOR. Next, we present the details of the GALOR mechanism.

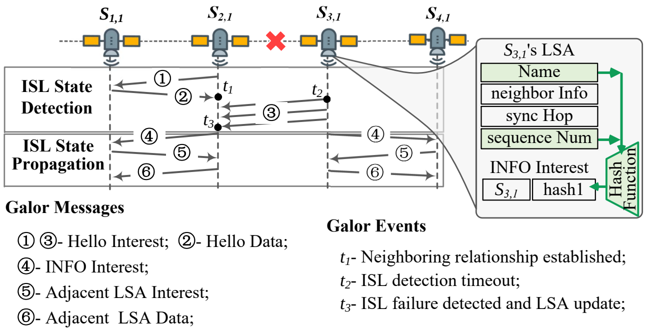


Fig. 3 – Illustration of routing mechanism in GALOR.

5. DESIGN DETAILS OF GALOR

In this section, we first introduce how to build the GALOR routing to guide the forwarding of interest packets. Then, we describe how GALOR retransmitted interest.

5.1 Design of GALOR mechanism

We present how the GALOR mechanism constructs the routing table from the following three perspectives, i.e., ISL state detection, routing information dissemination, and routing table calculation.

5.1.1 ISL state detection

GALOR adopts the hello mechanism to detect the ISL state (i.e., ISL establishment and failure).

- **ISL establishment:** A GALOR satellite sends a hello message to adjacent satellites in the ISL establishment process. When the satellite receives a response, i.e., a hello data message, from an adjacent satellite, it changes the ISL connectivity status to active.

- **ISL failure:** The GALOR satellite periodically sends a hello interest message to each neighbor (i.e., five seconds). When a hello interest is timed out, the satellite will try sending it a few times (i.e., three times). If there is no response from the neighbor during the period, the connectivity between the adjacent satellites is assumed to be unavailable. Then, the GALOR will initiate an *Adjacent LSA* and conduct the LSA synchronization process.

As shown by Step ① in Fig. 3, the GALOR satellite $S_{2,1}$ sends a hello interest to satellite $S_{1,1}$ in the ISL establishment procedure. Then, it receives a *hello data*, as illustrated by Step ② in Fig. 3. To this end, $S_{2,1}$ changes the connectivity status to active at t_1. In the ISL failure detection process, as shown by Step ③ in Fig. 3, the satellite $S_{3,1}$ sends a periodic hello interest to $S_{2,1}$ at time t_2. $S_{3,1}$ will try sending the hello interest three times at the interval when the hello interest is timed out. Accordingly, GALOR will declare the neighbor status as inactive at time t_3, as illustrated in Fig. 3. At the same time, the satellite initiates an adjacent LSA and carries out the LSA synchronization process.

5.1.2 Routing information dissemination

GALOR disseminates ISL state within a predefined range by controlling the propagation radius instead of the entire constellation, improving routing stability and decreasing control overhead (to be quantitatively evaluated in Section 6.2). Specifically,

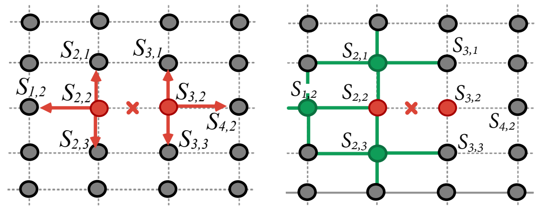
- **ISL state change notification:** GALOR uses a special interest message (i.e., "*INFO Interest*" in Fig. 3) to notify the ISL state change when the GALOR satellite detects ISL state change. Particularly, the ISL state change can only be notified within a small number of hops in LEO satellite networks. In this case, each GALOR satellite only maintains the real-time states of its nearby ISLs but does not know whether the other ISLs (far from it) function normally. Moreover, the *INFO interest* contains the hash of the LSA name and sequence number. As a result, the *INFO interest* carries only a few bits instead of the full LSA name, yielding less control protocol, as illustrated in Fig. 3.

- **ISL state synchronization:** When the GALOR satellite receives the INFO interest message, it will check the LSA's freshness by comparing the hash value, as illustrated in Fig. 3. Then, the GALOR satellite retrieves the latest LSA by sending the *adjacent LSA interest* message to the neighbor satellite. Eventually, the *adjacent LSA data* is returned to the satellite that sends the *adjacent LSA interest*. To this end, the GALOR satellite updates its LSDB and reconstructs the routing table.

We illustrate the ISL state synchronization under GALOR with the help of Fig. 3. Specifically, the GALOR satellite $S_{3,1}$ will create a new version of LSA when the ISL failure between $S_{2,1}$ and $S_{3,1}$ is detected at the time t_3. Then, the satellite $S_{3,1}$ generates an INFO interest and sends it to adjacent satellite $S_{4,1}$ (Step ④), which contains the hash of the LSA name, as shown in Fig. 3. When satellite $S_{4,1}$ finds that the LSA is fresh via the hash value of the INFO interest, it then sends an adjacent LSA interest for requesting the adjacent LSA data (Step ⑤). Eventually, the satellite $S_{3,1}$ returns the adjacent LSA data that carried the desired LSA information to adjacent satellite $S_{4,1}$ (Step ⑥). In particular, the LSA dissemination range of GALOR is controlled by *sync hop*. For example, Fig. 4 shows the ISL state dissemination range with *syncHop* = 1 and the maintained ISL state information, respectively. Specifically, as shown in Fig. 4(a), the satellite $S_{2,2}$ maintains the adjacent LSAs from satellite $S_{2,1}$, $S_{1,2}$, and $S_{2,3}$. Accordingly, as shown in Fig. 4(b), the satellite $S_{2,2}$ can get the ISL states of green ISL since each satellite maintains one hop ISL state.

5.1.3 Routing table calculation

Each GALOR satellite will calculate the routing table (for guiding interest forwarding) based on the collected localized fine-grained adjacency information (i.e., adjacent



(a) Sync Hop = 1 (b) Maintained ISLs state

Fig. 4 – ISL state synchronization in GALOR within limited hops.

LSA) and global view neighbor relation. Specifically, a GALOR satellite uses a generalization of the shortest path first algorithm to calculate the routing table. First, each GALOR satellite gets the number of links, which denotes the number of calculation iterations. Then, the satellite selects one of the links to calculate the cost to reach every inner-group satellite using Dijkstra's algorithm. This process is repeated for every available ISL. In this process, those ISLs far from this satellite are presumed to be working normally by default (i.e., global view assist). Note that the satellite also ranks the next hops for each satellite based on their respective cost, similar to NLSR.

Each entry of the routing table in a GALOR satellite is quintuple $\langle Dest, Content\ name, Next\text{-}hop, Cost\rangle$. Specifically, *Dest* is the NID of the destination satellite in the satellite network, *Content name* is the name of the content provided by the destination, *Next-hop* is the NID of the next-hop satellite, *Cost* is the cost of the path to a specific destination.

5.2 Proactive interest retransmission

In LEO satellite networks with intermittent ISLs, the ISL failure may destroy the content retrieving route recorded by the corresponding PIT entries in the NDN communication model. This phenomenon becomes severe in large-scale LEO satellite networks. Our proposed GALOR will overcome this drawback by resending the interest packets to reconstruct the destroyed content delivery path, as shown in Fig. 2. GALOR adopts the following two-fold designs to achieve this goal:

- *PIT with ingress and egress interfaces:* The GALOR mechanism slightly revises the PIT compared to NLSR. Specifically, each GALOR satellite records both the ingress and egress interfaces of the interest packet. In this case, the GALOR satellite knows which interface it will receive the corresponding data packet from and which interface it should forward the received data packet to.
- *Interest retransmission triggered by ISL failure:* Each GALOR satellite will detect the ISL states via the aforementioned hello interaction with its neighbors. Once an ISL failure is detected, GALOR satellite will update its routing table and check its current PIT entries. If there is a PIT entry whose egress interface corresponds to the failed ISL, then the GALOR satellite will retransmit an interest packet associated with the content name of this PIT entry. The retransmitted interest may reach the provider or may be aggregated during the packet forwarding. Thus, the content delivery path could be quickly reconstructed in response to ISL failures.

Algorithm 1: Proactive Interest Retransmission Scheme

```
   /* Process Interest packet                          */
1  if Cache store miss then
2      if PIT miss then
3          Find the egress interface of the next-hop
             based on routing table
4          Create a PIT Interest with ingress and
             egress interfaces
5      else
6          Add ingress interface to the exist PIT
7      Send the Interest packet to egress interface
8  else
9      Find the ingress interface of the Interest
         according to PIT entry
10     Send the Data packet back through the ingress
         interface
   /* Process Data packet                              */
11 if Cache store miss then
12     Add the content into cache store
13 if PIT miss then
14     Drop the Data packet
15 else
16     Find the ingress interface of the Interest
         according to PIT entry
17     Send the Data packet back through the ingress
         interface
   /* Process re-send Interest packet                  */
18 Get the interface from an ISL failure signal
19 Find the forwarded Interests based on the
     interface in PIT
20 Re-send an Interest packet according to routing
     table to the content provider
```

Based on the above description, we now introduce the major procedure of the packet process in GALOR, as shown in algorithm 1. It mainly consists of three phases:

- **Process interest and data:** Lines 1-10 and Lines 11-17 present the process of interest and data packet forwarding, which inherits the basic communication model of NDN, respectively. In particular, the GALOR satellite records both the ingress and egress interfaces of the interest packet.
- **Process resend interest packet:** Lines 18-20 introduce how the GALOR satellites resend interest packets when the interface down signal is detected.

Overall, GALOR outperforms ICN-based NLSR in terms of addressing the occasional ISL failure. Moreover, GALOR

Table 1 – Parameters in satellite constellations

Systems	Total sats	Orbits	Sats per orbit	Inclination (°)	Altitude (km)
Iridium	66	6	11	86.4	780
OneWeb	720	18	40	87.9	1200
Starlink	1584	72	22	53	550

also inherits the in-network caching and interest aggregation functionalities of NDN, thus achieving more efficient content delivery in the traffic-sharing pattern than IP-based routing. Next, let us evaluate the routing performance of the GALOR.

6. PERFORMANCE EVALUATION

We evaluate the performance of our proposed GALOR mechanism via packet-level experiments on OMNeT++.

6.1 Simulation setup

Constellation setting: We evaluate the routing performance of GALOR on three types of typical constellations with different constellation scales, as shown in Table 1:

- *Iridium constellation* [1] is a polar-orbit constellation with the inclination 86.4°. It consists of 66 satellites that fly along six orbital planes (i.e., 11 satellites on each orbit plane). The satellites are orbiting at an altitude of 780 km.
- *OneWeb* [2] is also a polar-orbit constellation with 720 satellites flying along 18 orbital planes. The orbit altitude is 1200 km.
- *Starlink constellation* [3] is a well-known, large-scale constellation. We consider the first shell of Starlink, which consists of 1584 satellites on 72 planes at 53°inclination. The orbit altitude is 550 km.

In our experiments, each satellite in the constellation has at most four ISLs (i.e., intra-plane and inter-plane ISLs). Moreover, we simulate occasional ISL failures by randomly generating the failure events according to a Poisson process with a specific rate λ to simulate the topology dynamics of satellite networks. Each failed ISL will recover after τ seconds (i.e., five seconds). The payload of each data packet is 1 KB. We consider 10 Mbps for all links (i.e., ISL and GSL) for simulation convenience.
Evaluation metric: We first evaluate the convergence time and control overhead in our simulation in Section 6.2. We then compare the packet delivery performance in Section 6.3. Specifically, we will assess GALOR under different traffic patterns[2] and ISL failure rates (i.e., {0, 1, ..., 20}), respectively.
Comparative methods: We compare GALOR's performance with the following state-of-the-art methods:

- *OSPF* [30] is a classic IP-based link-state routing protocol, widely used to distribute routing information on the Internet. Each OSPF node disseminates its link state changes within the entire network in a push manner. Some routing protocols (e.g., OPSPF [10]) designed for LEO satellite networks are based on OSPF. Thus, they can predict topology changes in LEO satellite networks. Particularly, in our experiments, the OSPF integrates the ISL state detection with the predictable LEO satellite network topology changes.
- *ASER* [21] is an area-based satellite routing protocol based on OSPF, which employs an area division scheme to restrict the ISL state change within the corresponding area.
- *NLSR* [15] is an NDN-based link-state routing protocol to guide interest packet forwarding, a counterpart to OSPF. Particularly, NLSR uses the interest/data packets to synchronize the link state changes within the entire network in a pull fashion.

[2] We use UxPy to denote the traffic pattern, which represents that x users request the content from y provider(s).

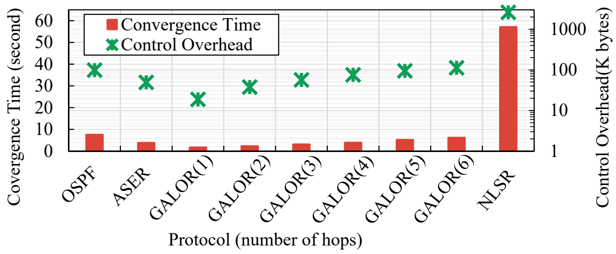


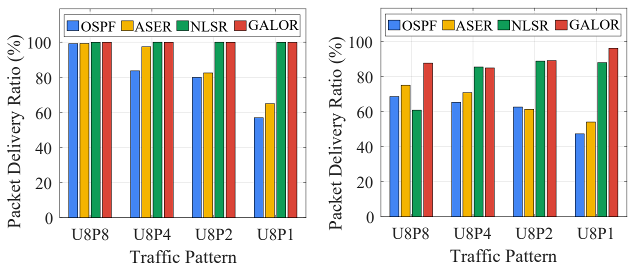
Fig. 5 – Convergence time and control overhead achieved by OSPF, ASER, NLSR and GALOR(k), where k represents the number of synchronization hops.

Every evaluation is carried out on a Sugon server with a Ubuntu 20.04 LTS in the virtual machine environment (VMware ESXi, 6.5.0).

6.2 Convergence time and control overhead

Recall that GALOR updates the ISL state advertisement within a limited synchronization hops when the ISL state change is detected. Hence, we will evaluate the impact of the number of synchronization hops on GALOR. Particularly, the Iridium constellation is divided into two areas, i.e., 33 satellites per area.
Fig. 5 plots the convergence time and control overhead results. The horizontal axis corresponds to the four types of routing mechanisms above. Particularly, we consider the impact of synchronization hops on routing convergence time and control overhead under the GALOR mechanism (i.e., $\{1, 2, .., 6\}$). We obtain three critical observations based on Fig. 5:

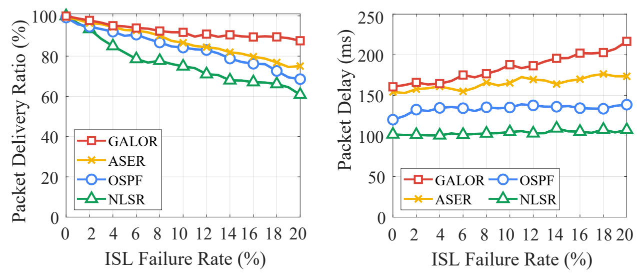
- Comparing GALOR with OSPF in Fig. 5, we can see that GALOR achieves the shortest convergence time and the smallest control overhead since it propagates the ISL state in a predefined synchronization hop. However, GALOR achieves a comparable convergence time to OSPF when GALOR announces the ISL state change globally since both of them adopt



(a) ISL failure rate 0%

(b) ISL failure rate 20%

Fig. 6 – Average PDR under different traffic patterns.



(a) Average PDR

(b) Average packet delay

Fig. 7 – Performance under different ISL failure rates in point-to-point traffic pattern (U8P8).

an event-trigger manner to disseminate ISL state changes.

- As shown in Fig. 5, ASER's convergence time and control overhead is higher than that of GALOR when the predefined number of synchronization hops is less than three. However, GALOR is higher than ASER's when the number of synchronization hops is more than three. The reason is that as the number of the ISL state changes synchronization hops increases, GALOR's ISL state changes are propagated beyond ASER.

- Comparing GALOR with NLSR in Fig. 5, we find that GALOR outperforms NLSR since NLSR synchronizes the ISL state in a periodic hop-by-hop pull-based manner via LSA interest/data, resulting in longer convergence time and greater control overhead.

6.3 Packet delivery performance

We evaluate the packet delivery performance of OSPF, ASER, NLSR, and GALOR(3) under the Iridium constellation. Particularly, we randomly generate the ISL failure events according to the Poisson process with different rates (i.e., {0, 1, ..., 20}) to simulate the satellite network topology dynamics.[3] Moreover, we conducted 20 sets of experiments and calculated their average.

Performance under different traffic patterns: Fig. 6 plots the average Packet Delivery Ratio (PDR) achieved by OSPF, ASER, NLSR, and GALOR. The horizontal axis represents the traffic patterns {U8P8, U8P4, U8P2, U8P1}, which vary from point-to-point pattern to content-sharing pattern. Hence, the in-network caching of NLSR and GALOR may play an increasing role during this change. We obtain two critical observations based on Fig. 6:

- As shown in Fig. 6, we observe that GALOR outperforms OSPF, ASER, and NLSR under the four traffic patterns. Specifically, from Fig. 6(b), we find that GALOR achieves up to 103.4%, 77.97%, and 9.33% higher PDR than OSPF, ASER, and NLSR in U8P1, respectively. The reasons are two-fold. First, GALOR is capable of addressing the occasional ISL failure via proactively resending interest packets, thus outperforming NLSR. Second, GALOR can reduce redundant content delivery via interest aggregation and in-network caching (thus outperforms OSPF and ASER).

- By comparing Fig. 6(a) with Fig. 6(b), we can see that the occasional ISL failure will decrease the average PDR of GALOR, OSPF, ASER, and NLSR. This is because the occasional ISL failure will deteriorate the routing stability and stateful packet forwarding. But GALOR still outperforms OSPF, ASER, and NLSR since it can proactively resend interest packets. We further plot the impact of the ISL failure rate in Fig. 7 and Fig. 8, respectively.

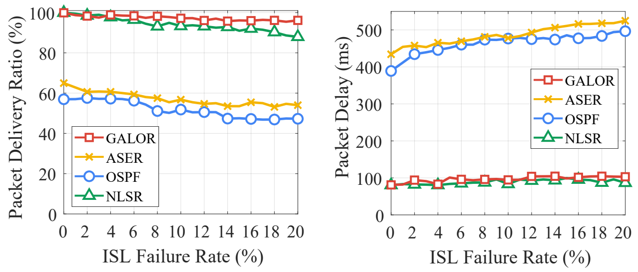
Performance under different ISL failure rates: Note that LEO satellite networks have strong topology dynamics. To evaluate the impact of ISL failure on packet delivery performance, we next investigate the impact of ISL failure on our proposed GALOR.

Fig. 7 and Fig. 8 investigate the impact of the ISL failure rate on packet delivery performance under the point-to-point traffic pattern (i.e., U8P8) and content-sharing traffic pattern (i.e., U8P1), respectively. The horizontal axis represents ISL failure rates (varying from 0 to 20%). Overall, the two sub-figures show that the occasional ISL failure will decrease the average PDR of all protocols but with different effects.

- For a point-to-point traffic pattern, Fig. 7(a) shows that the performance of NLSR decreases faster than OSPF, ASER, and GALOR. Specifically, our GALOR achieves up to 44.1% in PDR than NLSR. The reason is that the occasional ISL failure in LEO satellite networks will destroy the NDN's interest-forwarding route (i.e., PIT), degrading the content delivery performance. As for average packet delay, Fig. 7(b) shows that the packet delay of the above approaches increases as the ISL failure rate increases. The main reason is that the traffic will shift to an alternative ISL when the ISL fails, resulting in significant queuing delays.

- For a content-sharing traffic pattern, Fig. 8 shows that the PDR of GALOR is higher than that of NLSR (up to 9.32%). Moreover, GALOR outperforms OSPF

[3] In our experiments, the failed ISLs will recover after a short period, i.e., five seconds.



(a) Average PDR (b) Average packet delay

Fig. 8 – Performance under different ISL failure rates in point-to-point traffic pattern (U8P1).

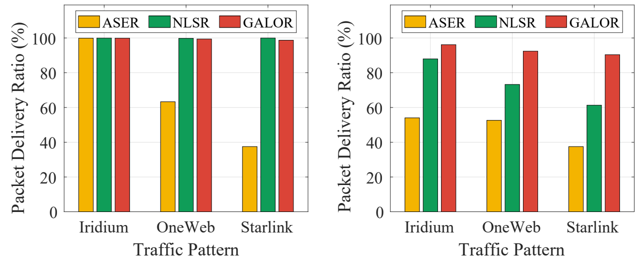
and ASER (up to 103.4% and 77.97%) in the U8P1 scenario. The reasons are two-fold. First, GALOR enables a proactive interest packet resending when the occasional ISL failure occurs, reconstructing failed PIT entries. Second, the in-network caching of the GALOR can reduce the content transmission cost and retrieval delay.

6.4 Evaluation of GALOR under large-scale constellation

Now we conduct the extra experiments to assess the performance of our proposed GALOR mechanism under different constellation scales. Specifically, we consider different scales of classic constellations, as shown in Table 1. Moreover, we divide the OneWeb and Starlink constellation with the same area division scheme for ASER, i.e., 9×10. Note that the number of orbits (or satellites) in the constellation may not be evenly divisible, creating a few areas larger than 9×10.

Fig. 9 illustrates the results of average PDR under different constellations. The horizontal axis represents three typical constellations under the content-sharing traffic pattern. From Fig. 9, we can see that GALOR outperforms the comparative mechanisms under different constellation scales. Specifically:

- Comparing GALOR with ASER in Fig. 9(a), we find that the GALOR achieves a higher average PDR than ASER up to 163.2%. This is because GALOR naturally supports in-network caching, enabling efficient content retrieval and reducing redundant content delivery in LEO satellite networks.
- From Fig. 9(b), we can see that the ISL failure will decrease the average PDR of ASER, NLSR, and GALOR. Moreover, the average PDR of GALOR is at least 9.3% higher than that of NLSR, while this value is 77.9% when compared to ASER. The reasons are two-fold. First, GALOR disseminates the ISL state within a predefined range instead of the entire constellation, reducing routing table recalculation and improving routing stability. Second, GALOR is capable of reconstructing failed PIT entries by interest retransmission in response to the occasional ISL failures. This improves the content delivery performance of the GALOR mechanism.



(a) ISL failure rate 0% (b) ISL failure rate 20%

Fig. 9 – Content delivery performance under different constellation scales in content-sharing traffic pattern (U8P1).

7. CONCLUSION

In this paper, we focused on achieving efficient content delivery in LEO satellite networks by leveraging the determined neighbor relation. We first elaborate on the typical topology characteristics of LEO satellite networks. We then present the design of Global view Assisted Localized fine-grained Routing (GALOR), which follows the NDN-based routing paradigm. Specifically, GALOR announces the ISL state change within predefined hops rather than the entire constellation. This reduces routing convergence time and control overhead. Third, GALOR reconstructs failed Pending Interest Table (PIT) entries by resending the interest packets in response to the occasional ISL failures. This improves the content delivery performance of the GALOR mechanism. Simulation results indicate that GALOR is capable of achieving fast convergence time with little control overhead. Furthermore, GALOR outperforms IP-based (OSPF and ASER) and NDN-based (NLSR) routing up to 103.4% in terms of average packet delivery ratio.

ACKNOWLEDGEMENT

This work was supported by National Natural Science Foundation of China under Grants 62202021, 62225201, and 62271019, in part by the State Key Laboratory of Software Development Environment under Grant SKLSDE-2022ZX-18.

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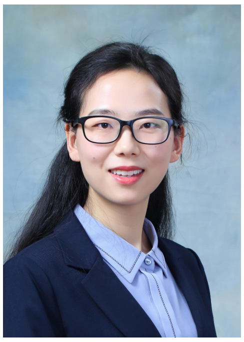

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