NDN in Large LEO Satellite Constellations: A Case of Consumer Mobility Support

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ABSTRACT

Large low Earth orbit (LEO) satellite constellations are intended to provide global low-latency high-bandwidth Internet connectivity. Due to their large scale and high mobility nature, networking is a big challenge. In this paper, we investigate applying Named Data Networking (NDN) to this scenario. Specifically, we discuss that NDN's architectural benefits, such as adaptive forwarding, in-network caching, off-the-grid communication, data mule service, in-network/edge computing, mobility support, and data-centric security, make it a promising candidate. Moreover, we focus on studying NDN's consumer mobility support. Specifically, NDN's in-network Interest retransmission can quickly react to satellite handovers. However, we make an observation that Interest routing paths before and after satellite handover may not overlap, hence underusing NDN's in-network caching. Therefore, we direct retransmitted Interests due to handovers to the previous connected satellite via forwarding hint. Simulation results show that the studied approaches can decently improve the consumers' performance and reduce the network traffic, achieving better consumer mobility support.

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CCS CONCEPTS

• **Networks** → **Network architectures**; **Network mobility**.

KEYWORDS

ICN; NDN; Large LEO Satellite Constellations; Satellite Networks; Consumer Mobility, Mobility Management

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1 INTRODUCTION

While the idea of providing Internet from space using large constellations of low Earth orbit (LEO) satellites has been around since the decade of the $90's$, there has been renewed interest in recent years, inspired in large part by a great number of proposals [2–4, 6, 11, 21], and several technology advances, including low-cost satellite manufacturing and launching capabilities, and high-speed link-tracking technology. For example, the US Federal Communications Commission (FCC) has approved $12,000$ Starlink satellites [19]. In addition, SpaceX disclosed that each launch carries 60 satellites, and SpaceX has launched 1740 satellites with 1624 of them in orbit by the end of July 2021 [5].

Large LEO satellite constellations are proposed to provide global low-latency high-bandwidth Internet connectivity. To achieve low-latency connectivity, LEO satellites are launched at low altitudes (160-2000 km), hence moving fast relative to the ground. Therefore, continuous connectivity requires a large number of satellites. In addition, ground stations and users have frequent handovers/disconnections in communications with satellites. For example, a LEO satellite at 500 km altitude travels at 7.6 km/s and it takes about 95 minutes to orbit the Earth, resulting in a handover every 5 minutes approximately [14].

Due to its very large scale and high mobility nature, networking in LEO constellations is a big challenge. We hypothesize that today's LEO constellations can be equipped with a certain amount of computing and storage resources (Section 2.2). Therefore, we are motivated to investigate applying Named Data Networking (NDN) [37] in this scenario. Specifically, we argue that NDN's architectural benefits, such as adaptive forwarding, in-network caching, off-the-grid communication, data mule service, in-network/edge computing, mobility support, and data-centric security, provide an effective and efficient networking system specifically for LEO constellations (Section 2.2).

Moreover, we focus on studying NDN's consumer mobility support in this scenario. As pointed out by [14], building an IP-based LEO satellite network faces significant challenges in mobility management, including location management and handover management. In contrast, NDN provides a data-centric architecture with a pull communication model, which can better assist users (consumers) to retrieve data in mobile scenarios, i.e., users simply retransmit requests (Interests) after a satellite handover, reducing the complexity of location and handover management.

However, this basic mobility support incurs extra delays and slows down future requests rates, because timeouts are used as signals for network congestions [28]. To improve this, in-network Interest retransmission was proposed and studied in terrestrial wireless mobile scenarios [12]. Because a consumer's forwarder is able to detect the link change and retransmit stored software state, i.e., Interest, in-network Interest retransmission can minimize the negative impact caused by application Interest retransmission.

Furthermore, we make an observation that the performance of Interest retransmission due to handovers depends on the joint distance between Interest routing paths before and after a handover. For example, if a retransmitted Interest uses the previous path, it will benefit from the previous data retrieval; if a retransmitted Interest uses a totally different path, the transmission of the previous Interest and the corresponding Data transmissions are wasted.

This observation motivates us to study the differences between Interest routing paths due to handovers. With a real satellite constellation simulation that applies the shortest path routing in a grid satellite topology, we find that if a sequence of Interests are routed by inter-orbital-plane satellites, the retransmitted Interests due to handovers use a totally different routing path, hence underusing NDN's in-network caching (Section 3.2). Therefore, we propose to direct retransmitted Interests due to handover to the previous connected satellite. More specifically, we use *forwarding hint* to achieve this [10] (Section 3.3).

Regarding evaluation, we implement in-network Interest retransmission and the one with forwarding hint in NFD [9], an NDN-aware software forwarder. Specifically, we simulate the movement of a large LEO satellite constellation used in Starlink and generate snapshots of satellites' positions to represent different scenarios. The snapshots are then fed to ndnSIM [25], a simulator built on top of NS-3 with NFD imported. The three aforementioned approaches, application Interest retransmission, in-network Interest retransmission, and the one with forwarding hint, are simulated in ndnSIM. Simulation results show that directional routing with forwarding hint can improve in-network Interest retransmission, and both can decently improve the consumers' performance and reduce the network traffic, compared to NDN's native mobility support (Section 5).

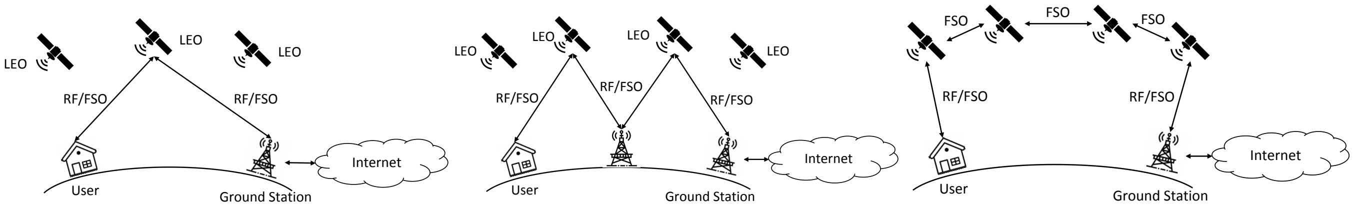
To summarize, the contributions of this work are as follows.

- We investigate applying NDN to large LEO satellite constellations, and discuss NDN's potential architectural benefits specifically for this scenario, including adaptive forwarding, in-network caching, off-the-grid communication, data mule service, in-network/edge computing, mobility support, and security.
- We investigate the consumer mobility problem of NDN in large LEO satellite constellations. Specifically, we study and compare NDN's native consumer mobility support, i.e., application Interest retransmission , and in-network Interest retransmission.
- With a satellite constellation simulation, we make an observation that inter-orbital-plane routing algorithm uses a totally different path after a handover, hence underusing NDN's in-network caching. To address this issue, we propose to direct the retransmitted Interests due to satellite handovers to the previous accessed satellite via a forwarding hint.
- We implement in-network Interest retransmission, and the one with forwarding hint in NFD, and simulate the aforementioned three approaches in ndnSIM. Moreover, we implement a simulation model to generate snapshots of satellites' positions as simulated scenarios, given an existing large LEO satellite constellation.

2 BACKGROUND AND MOTIVATION

2.1 Large LEO satellite constellations

2.1.1 Hardware Resources. Traditionally, satellites are known to have limited weight, hence are equipped with limited



(a) one relay LEO/ground station **(b) multiple relay LEOs/ground stations** **(c) multiple interconnected relay LEOs**

Figure 1: Three models of LEO Internet constellations with different requirements of inter-satellite links

capabilities. However, according to the public information disclosed by SpaceX in June 2020, each launch carries 60 satellites containing 4, 000 Linux computers [31], indicating that a decent amount of general operating systems and programming environments have been provided in today's LEO constellations. Although the specification of each Linux computer has not been disclosed, we hypothesize that each LEO satellite can be equipped with a certain amount of computing and storage resources, which provides possibilities to run NDN and other services.

2.1.2 Connectivity. Due to lack of dedicated inter-satellite links (ISLs) [18], the deployment of large LEO satellite constellations has different stages, which are summarized as follows (depicted in Fig. 1).

One relay LEO and ground station. This is the basic networking model for LEO satellites to provide Internet access (Fig. 1a). In this model, each ground station has Internet connectivity. Each LEO satellite extends the Internet connectivity from the ground station to the covered area that is able to communicate. According to [22], both Radio Frequency (RF) and Free Space Optical (FSO) communication technologies can be used for the communication between ground and satellite (i.e., uplink and downlink). RF provides lower bandwidth, e.g., the commonly used Ku-band can achieve 17.2 Gbps, while FSO communication can achieve 10^5 times higher throughput. However, the performance of FSO is more sensitive to environmental factors than RF, e.g., clouds may disrupt or block the optical signal.

Multiple relay LEOs and ground stations. Depicted in Fig. 1b, this model extends the first networking model to provide low-delay wide area networking without requiring ISLs, which may not be available at early deployment [18].

Multiple interconnected relay LEOs. As illustrated in Fig. 1c, in addition to uplink and downlink, each satellite is equipped with inter-satellite links. Regarding ISLs, FSO communication technology is used to provide high capacity communications. As long as two satellites have line of sight, they are capable to communicate with optical transmitters. One common setting is that each satellite connects to four neighbor satellites, two are on the same plane and two are on different planes [17]. For intra-plane neighbor satellites, they are moving towards the same direction with the same speed, hence are relatively static. For inter-orbital neighbor satellites, they change periodically, hence the links are changing periodically. To set up an optical link, it requires the procedure of acquisition, tracking and pointing [22], which we assume takes nontrivial time, hence breaking the continuous connectivity for inter-orbital links.

We first discuss NDN's architectural benefits that can be applied to all three stages. Then we focus on the third stage to study NDN's consumer mobility support.

2.1.3 Routing. Although the network topology of large LEO satellite constellations is highly dynamic, the moving pattern of each orbit is predictable. Therefore, given a timestamp, the network snapshot of a constellation (with ground stations) can be computed, and then Dijkstra's algorithm [15] can be applied to compute the shortest routing path between two nodes. The computed results are effective for a short period of time (e.g., a few hundred milliseconds), then required to be recomputed due to the high mobility. Given the envisioned scale of LEO satellite constellations and today's computing capability, there is no difficulty in running Dijkstra for all traffic sourced by a ground station to all destinations every 10 *ms* [17]. In this work, we assume that each satellite forwards traffic based on the Dijkstra shortest routing path computed over the constellation. However, we realize the potential issues of running shortest-path routing protocols in this scenario, and argue for a better solution of NDN's adaptive forwarding.

2.2 Why NDN

This section first briefly introduces NDN, then discusses potential benefits of NDN for LEO constellations.

2.2.1 A brief introduction of NDN. Different from an IP network that pushes packets to a destination, NDN uses a pull communication model, which requires users to send requests (i.e., *Interest* packets) first. An Interest packet carries a name; an NDN network forwards it based on its name; once the

Interest is matched by a *Data* packet (also carries a name), the Data packet will be forwarded back using the reverse path. In NDN, applications define and name Data packets, and the NDN router processes packets based on their names. More details are explained in [8, 37].

2.2.2 NDN's architectural benefits for LEO constellations.

Adaptive Forwarding. An NDN node is able to observe data retrieval performance of past Interests and use it to adjust forwarding decisions for future Interests [24, 34]. This feature allows an NDN node to quickly adapt to the network conditions and pick the best path reactively, which can potentially improve the efficiency of network resources in LEO constellations. As explained in Section 2.2, LEO constellations have multiple paths between two endpoints, given that each satellite has both uplink and downlink, and four neighbor orbit links. Next, the uplink and downlink can use both RF and FSO communication technologies, which perform differently under uncertain weather conditions. Last, inter-orbital optical links change over time and take non-trivial time to set up. Therefore, the best path between two end hosts may change frequently and unpredictably over time, leading to significant challenges to shortest-path routing protocols. In contrast, NDN's adaptive forwarding has potentials to achieve better performance under these dynamics with low cost.

In-network caching. NDN provides in-network caching for both Interest and Data. Interest caching allows data multicast, because Interests with the same name can be aggregated without duplicated forwarding, and the returned Data packet can satisfy all Interests. This built-in multicast reduces network traffic. Data caching can assist content distribution, especially for popular content, such as popular software updates and videos. Although LEO constellations have potentials to be equipped with decent hardware resources, they are still limited compared to terrestrial networks. NDN provides an architectural solution to maximize network resources in this scenario for applications such as content distribution and live streaming.

Off-the-grid Communication. Satellite networks can provide not only Internet connectivity, but also local area connectivity, which is crucial for many scenarios, e.g., users use the same satellite to communicate among themselves in remote areas. Most of today's applications assume Internet connectivity is available, and they are configured to communicate with pre-defined host names or addresses. Therefore, they are unable to share data among themselves directly without Internet connectivity, which is referred as the off-the-grid communication. Some applications are designed to work with local area connectivity, but they require ad hoc and complex mechanisms, such as Bonjour [20], Bluetooth [1], and Zigbee [7]. NDN provides a unified data retrieval protocol for applications, allowing them to retrieve data from anywhere, either from the Internet or a nearby device. Application developers are free from choosing between Internet and off-the-grid communication technologies [23].

Data mule services. LEO satellites can serve as data mules to move data around, given that they have high speed. This feature is useful in the early deployment stage when continuous global connectivity is not available. The main requirement of this service is store-and-forward capability [16], which can be naturally supported in NDN architecture, because of NDN's data-centric model with in-network caching and pull communication semantics. Specifically, to support data mule service, an NDN node has to hold Interest and Data, and send them to the targeting face when it is up. This requirement can be easily implemented with NDN's in-network caching and customizable forwarding strategy support. Moreover, this DTN-style communication service is part of NDN's unified data retrieval model, which can reduce burden on application developments.

In-network/edge computing. Hypothetically, LEO satellites can be equipped with more computing resources not only for routing and forwarding (Section 2.2). One potential usage is to provide in-network/edge computing in assisting data collection from different entities, such as scientific data collected at the Arctic, climate data collected from weather satellites, and particles collected from space telescopes. These entities collect a large volume of raw data in a distributed way, which needs to be sent to labs for further study. LEO constellations provide a convenient approach to transfer these data. To improve data transferring efficiency, various algorithms can be applied to raw data, such as duplicate removal, noise filtering, and algebraic operations. These optimizations require an in-network/edge computing infrastructure. NDN can reduce the complexity of such infrastructure, e.g., it can provide efficient solutions for resource discovery, compute re-use, mobility and security management [26].

Security. NDN's data-centric security is the foundation of the above benefits. An NDN Data packet is the unit and the starting point for authenticity and confidentiality, therefore it can be authenticated and accessed no matter where it is retrieved, either from in-network caching, a local device, or data mule service. Specifically, the relation among Data packets, signing keys, and names are defined by trust schema [35]. Additionally, name-based access control encrypts data at production, and allows users who have the decryption key to access data [36]. Regarding forwarding, NDN secures FIB entry creation, either from routing protocols [33] or the self-learning mechanism [30].

2.3 NDN's mobility support

2.3.1 Consumer mobility support. NDN's built-in consumer mobility support allows applications to retransmit Interests after timeouts, which natively deals with satellite handovers. However, this basic support delays data retrieval during handovers. Moreover, applications use Interest timeouts as congestion signals [28], and thus it will slow down Interest sending rates. To improve this, in-network Interest retransmission was proposed [12]. Because a consumer's forwarder is able to detect link change and retransmit stored software state, i.e., Interest, in-network Interest retransmission can minimize the negative impact caused by application Interest retransmission. However, it is unknown how these mechanisms perform in large LEO satellite constellations, which is investigated in this paper.

Moreover, we make an observation that the performance of Interest retransmission depends on the joint distance between Interest routing paths before and after the handover. For example, if a retransmitted Interest uses the previous path, the previous data retrieval will be utilized; if a retransmitted Interest uses a totally different path, the transmission of the previous Interest and the corresponding Data is wasted. This observation triggers our first question, *how different are Interest routing paths before and after the handover in large LEO satellite constellations.* We study this question in section 3.2.

2.3.2 Producer mobility support. NDN's producer mobility support is more complicated than consumer mobility support. As summarized in [38], the two major approaches are keeping track of the movement and reachability of mobile producers, and make the data generated by mobile producers available at a reachable named location. For example, KITE provides a secure, locator-free, and network-layer producer mobility support [40]; MNDN uses a global name resolution service with a forwarding hint to achieve producer mobility support with scalability taken into consideration [27]. This work only focuses on NDN's consumer mobility support in large LEO satellite constellations.

3 DESIGN RATIONALE

3.1 In-network Interest retransmission

NDN's native consumer mobility support allows applications to retransmit Interests after timeouts, which can retrieve data after a handover without relying on extra network mechanisms. However, this basic support incurs extra delays and slows down future requests rates. This problem becomes severe in large LEO satellite constellations due to their frequent handovers.

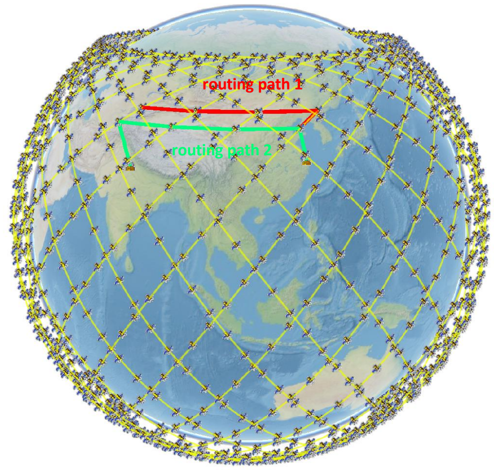


Figure 2: An example of non-overlapping Interest Routing paths before and after a satellite handover. This figure is drawn using Cesium [13], an open platform for 3D geospatial data. The LEO constellation parameters are shown in Table 1.

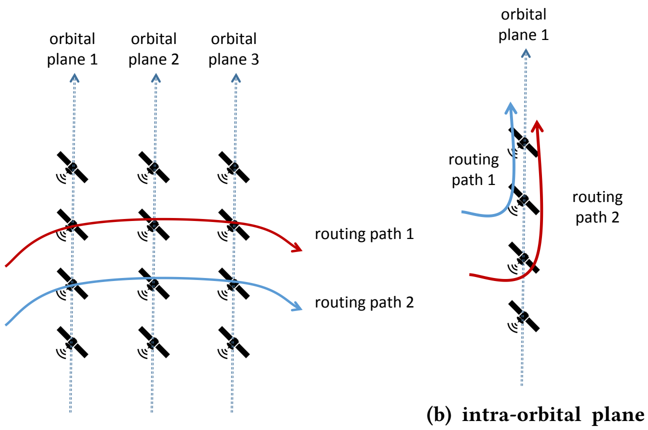
To improve this, in-network Interest retransmission was proposed, and studied in terrestrial wireless mobile scenarios [12]. We investigate its usage in satellite constellations. After a satellite handover, a consumer connects to a new satellite. The forwarder at the consumer should detect the handover and retransmit the responding pending Interests to the newly connected satellite. Specifically, the forwarder either creates a new Face [1], or changes the link layer of a static fixed Face, which always communicates with a satellite. In both cases, the forwarder forwards the pending Interests, which have been forwarded to the previous satellite Face, to the (new) satellite Face.

3.2 Retransmitted Interest Routing Path

Intuitively, if retransmitted Interests follow the routing path of the previous transmitted Interests, they are likely to hit data cache, hence improving performance. However, this is not a common case in LEO constellations. Figure 2 shows an example of non-overlapping Interest routing paths before and after a satellite handover. Assuming the shortest path routing algorithm is used, routing path 1 in red is the one before a satellite handover, while routing path 2 in green is the one after the satellite handover. They use totally different orbits to forward packets.

To further study, we find that whether two Interest routing paths overlap, before and after a satellite handover, depends

[1]The new face here refers to an Interface or an abstraction of a remote point identification.



(a) inter-orbital plane routing

(b) intra-orbital plane routing

Figure 3

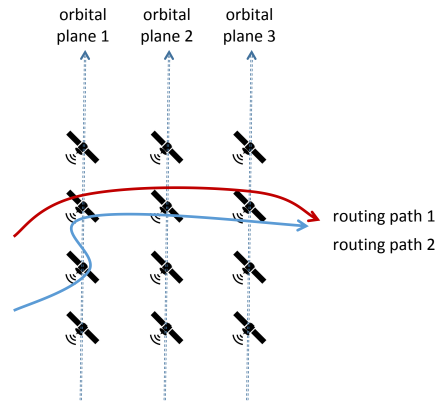


Figure 4: Directional routing via forwarding hint

on whether the routing path is an inter-orbital plane or intra-orbital plane. As shown in Fig. 3, if the routing path of a sequence Interests is inter-orbital, they will not overlap; if their routing path is intra-orbital, they will overlap. The former case wastes the efforts of the transmitted pending Interests before the handover, while the latter case can fully utilize their efforts because the retrieved data is on the Interest routing path after the handover. Note that a routing path may consist of satellites on both inter-orbital planes and intra-orbital planes, and still follows the finding.

3.3 Directional routing via forwarding hint

Our idea is to route retransmitted Interests due to handovers back to the previous accessed satellite, so that the routing paths can overlap (shown in Fig. 4). To achieve the goal, we use *forwarding hint* [10, 39].

Forwarding hint is a locator carried in Interest, indicating "where" to forward the Interest. The forwarding hint was originally designed to tackle the routing scalability issue in NDN. With forwarding hint, NDN's core networks can only announce locations as prefixes, which is more scalable than announcing data name prefixes. In this paper, we use forwarding hint as an approach to intentionally routing the retransmitted Interests back to the previous satellite. Then the following design issues have to be considered.

First, each satellite is required to announce its location identifier (e.g., `/router/sat23`) to neighboring nodes. To limit the announcing overhead, the announcing area can be constrained within a small number of hops (e.g., 3 hops), with the assumption that connected satellites during a handover are reachable within a small number of hops.

Next, the location identifier can be learned when the satellite connection is set up. When a user connects to a satellite, the user creates a new Face or updates an existing Face, which also records the locator of the satellite. Then, when a user connects to a new satellite, it can attach the location identifier of the previous accessed satellite as the forwarding hint to the retransmitted Interests.

Last, the employment of forwarding hints exposes a security issue named *cache poisoning*, i.e., a malicious user can prepare malicious or incorrect data at a controlled site; then the user intentionally requests the data by using the forwarding hint pointing to the site; as a result, the cached data along the request path will be "poisoned". To prevent this attack, one design is to limit in-network caching lookup on the combination of name and forwarding hint, instead of only on names. However, in our scenario, this attack does not exist because the forwarding hint points to a satellite router which was on the Interest path instead of a site. Therefore, the expected caching lookup should not take the forwarding hint into consideration.

To distinguish the processing behavior of the proposed forwarding hint, we propose to use different naming of forwarding hint. For example, the name of a site can be `/site/as039`, while the name of a satellite router is `/router/sat101`. The locator's name difference can indicate caching lookup to be different. Note that this mechanism requires each satellite to be uniquely named in the NDN network.

4 DESIGN DETAILS & IMPLEMENTATION

In this section, we describe and compare three mechanisms in handling satellite handover.

4.1 Application Interest retransmission

NDN's built-in consumer mobility support allows applications to simply retransmit Interests after timeouts, which handles satellite handovers without relying on any extra mechanism. This basic mechanism is simple, but incurs extra delays (timeouts plus data retrieval round trip time) and slows down Interest rates. We consider this mechanism as the baseline.

4.2 In-network Interest retransmission

4.2.1 Consumer Procedure. In-network Interest retransmission mechanism is added to the forwarder at consumers. After a satellite handover, the processing steps are described as follows.

- **Notification of new face creation**: The forwarder has to detect if a new Face connecting to satellite is created or not. The new Face will be created with its status set as "up", and the status of the previous satellite Face is set as "down". The creation of the new Face will send out a notification signal in the forwarder.
- **Add a default route**: On hearing the new Face creation notification, routing information base (RIB) manager creates a default route "/" to the new Face. The default route will be added to the forwarding information base (FIB). FIB will trigger the corresponding forwarding strategy under the default route "/" to take actions.
- **Pending Interest retransmission**: The triggered forwarding strategy checks if the pending Interests have been sent to the down satellite Face; if so, these Interests will be retransmitted to the new satellite Face.

4.2.2 Implementation. The notification of new face creation, and the corresponding forwarding strategy trigger are supported features in NFD [29]. We implement the action of adding a default route in RIB manager, and the action of retransmitting pending Interests to the new Face.

4.3 In-network Interest retransmission with forwarding hint

4.3.1 Consumer Procedure. The steps in this mechanism are the same as the previous one except for some changes in the following steps.

- **New face creation**: Each new satellite Face will associate with a forwarding hint, e.g., `/router/sat12`. The forwarding hint is learned during the satellite connection.
- **Interest retransmission**: the retransmitted Interests will be attached with a forwarding hint of the previous connected satellite.

4.3.2 Forwarding hint. The forwarding hint is an optional element of Interest format version 0.3 [32]. The element contains a list of name delegations. Each delegation implies that the requested Data packet can be retrieved by forwarding the Interest along the delegation path.

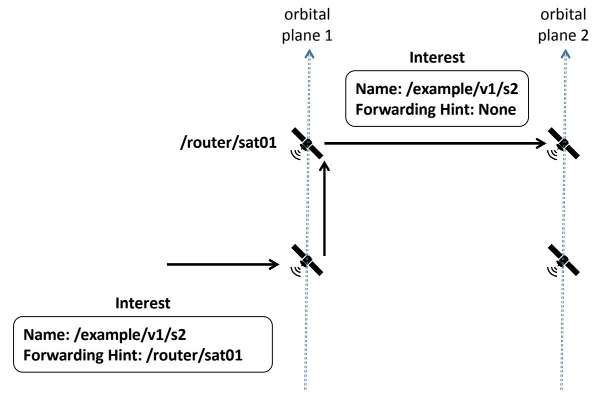


Figure 5: An example of forwarding processing with forwarding hint

4.3.3 Related Actions. In addition, this mechanism requires the following steps or changes.

- **Locator announcement**: Each satellite has to announce its locator to neighboring nodes. To minimize the announcement overhead, the reachability of locator announcement can be limited to a small number of hops (e.g., three hops).
- **Forwarding**: Interests carrying a forwarding hint should be forwarded according to the forwarding hint first. If the forwarding hint cannot find a match in FIB, they should be forwarded based on their names. When those Interests reach the target satellite pointed by the forwarding hint, the forwarding hint should be removed, and the Interests should be processed normally. An example is shown in Fig. 5.
- **Caching Lookup**: If a forwarding hint starts with a dedicated name prefix, e.g., `/router`, the forwarding hint should be ignored when looking up in-network caching. This is different from the current forwarding hint design and should be a key of CS lookup (analyzed in Section 3.3).

5 EVALUATION

We use simulations to evaluate the performance of our proposed mechanisms. Specifically, we use a LEO constellation setup from Starlink to form a network. Then, we use ndnSIM [25] for simulations. ndnSIM is built on top of NS-3 with NFD [9] (i.e., an NDN forwarder) ported.

Because ndnSIM does not provide a module to simulate LEO constellations, we develop an external program to generate a series of topology snapshots consisting of the positions of both satellites and ground users. The topology snapshots are input to ndnSIM, to simulate the movement of the LEO constellation.

Table 1: Constellation parameters

Description	*Settings*
Orbit height	550km
Inclination	53.8°
Number of orbit planes	24
Number of satellites per orbit plane	66
Minimum elevation angle	25°

Regarding scenarios, we simulate a consumer downloading a file from a producer. Both the consumer and producer are picked as two different cities globally. We focus on satellite handovers, i.e., when users change the access satellites. Then, we measure and compare the data retrieval performance of the three retransmission mechanisms: application Interest retransmission (AIR), in-network Interest retransmission (IIR), and in-network Interest retransmission with forwarding hint (IIR-FH). Data retrieval performance is evaluated via three metrics: the average data retrieval delay, the total number of retrieved data, and goodput ratio.

5.1 Experimental settings

5.1.1 Constellation parameters. The simulated LEO constellation is based on the settings of Starlink phase-1 deployment, whose constellation parameters are given in Table 1. Overall, a total number of 1584 LEO satellites are running at the height of $550km$ on 24 circular inclined orbits.

5.1.2 Link assignments. Each satellite has multiple downlinks, and four ISLs. Two ISLs are with neighbor satellites on the same orbit plane, and the other two are on adjacent orbital planes. Regarding user uplinks, a ground user can connect to only one satellite at a time. For simplicity, both ISLs and user uplinks are emulated with perfect point-to-point links, and the delay of each link is uniformly set to 10 milliseconds.

5.1.3 Routing. Given the constellation settings and the link assignments, we are able to compute the shortest routing path between any two satellites, given a snapshot of the topology. The snapshot is captured every minute.

5.1.4 Satellite handover strategy.

We use a simple satellite handover strategy, i.e., a ground user always prefers the nearest satellite on the same orbit plane as the current access satellite. A satellite is accessible only when it is above the elevation angle. If the current orbital plane does not have an accessible satellite, the user will check a different orbital plane for the nearest satellite. Given a geolocation and a constellation snapshot, we can calculate the access satellite of the geolocation via this strategy.

5.1.5 Consumer behavior. We use constant-bit-rate (CBR) consumers. The retransmission timer is set accordingly to the recently observed RTTs, and once a timeout occurs, a retransmission is scheduled using an exponential backoff timer. Both new and retransmitted Interests are queued before sending out at the constant speed. Hence Interest retransmissions reduce data retrieval speed. We use different Interest rates, between 50 to 300 Interests per second with a step of 50.

5.1.6 Scenario. We pick three major cities, Beijing (Asia), New York (North America), and São Paulo (South America), as the geolocation of consumers and producers, so 6 pairs of consumer and producer in total. Then, we calculate their access satellites with the shortest routing path in between every minute. Next, we collect performance metrics.

5.2 Results

We first evaluate satellite handovers, including their frequency and their impact on using forwarding hints. Then, we evaluate the performance of the three consumer mobility mechanisms. Specifically, the performance metrics are collected during the two seconds period of the handover, one second before and one second after.

5.2.1 Satellite handovers. Given the above scenario, Beijing, New York, and São Paulo experience 39, 40, and 32 handovers respectively, during one orbit period of 95 minutes, meaning that they have as frequent handovers as every 2-3 minutes. In addition, all three geolocations change a different orbital plane to access satellites once. This change indicates that it is possible that no direct link between two consecutive access satellites. Therefore, we calculate the average topological distance (i.e., the number of hops) between two consecutive access satellites for one orbit period, which are 1.64, 1.82, and 1.88 hops for Beijing, New York, and São Paulo respectively.

5.2.2 The average data retrieval delay. The average data retrieval delay refers to the elapsed time from sending the first Interest to finally receiving the requested data averaged over each successful data retrieval. Thus, it indicates a mechanism's ability to smoothen the handover process. Results under different consumer and producer location settings are shown in Fig. 6. Because results are similar under different consumer sending speed settings, we present here the results under the highest setting of 300 Interests/second. AIR performs significantly worse than the other two, as the retransmission (triggered by the timeout) under this mechanism is not conducted promptly after a handover. IIR and IIR-FH have comparable performance to each other. Considering the potentially different paths taken by the retransmitted Interests in IIR and IIR-FH, this phenomenon deserves a further

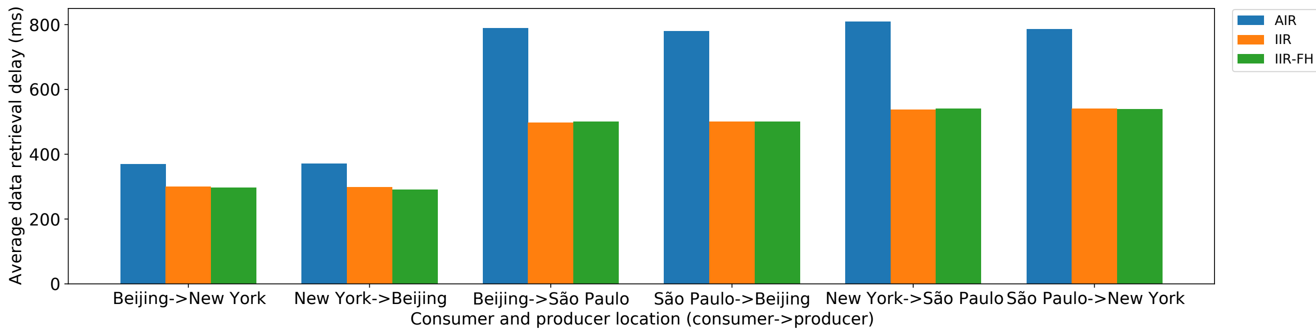


Figure 6: The average data retrieval delay vs. consumer and producer location, with consumer sending rate as 300 Interests per second

investigation. For each pair of locations, the delay is identical regardless of which one is the consumer. This should be credited to the use of symmetrical routing.

5.2.3 *The number of the retrieved data.*

The number of the retrieved data refers to the number of successful data retrievals, and reflects a mechanism's ability to mitigate the impact of handovers on application-level congestion control, and thus increase the overall data retrieval speed.

The performance of three evaluated mechanisms when consumer sending speed is 300 Interests per second is shown in Fig. 7. Across all consumer and producer locations, IIR and IIR-FH perform equally well, and significantly better than AIR. This is because IIR and IIR-FH seldomly require application retransmissions, and thus the consumer application can keep a steady data retrieval rate. As both IIR and IIR-FH belong to in-network retransmission mechanisms, they have quite close performances regarding the effect on reducing application retransmissions. It can also be observed that, for the same consumer location, only the performance of AIR is affected by producer locations. This is because a longer RTT (e.g., the average RTT between Beijing and New York is 258*ms*, while the average RTT between Beijing and São Paulo is 464*ms*) means that more Interests would be affected by a handover, and would thus produce more retransmissions and further reduce data retrieval speed with AIR.

The relationship between consumer sending speed and data retrieval speed for New York consumer and Beijing producer is shown in Fig. 8, while the results for other combinations are similar and not presented here. It can be observed that the amount of retrieved data grows linearly with consumer sending speed, and each mechanism grows at a different rate, which leads to higher download rate differences at higher consumer sending speeds (e.g., IIR and IIR-FH allow retrieving up to about 15% more data packets with consumer sending rate of 300 Interests per second).

5.2.4 *Effective data retrieval ratio.*

We define *effective data retrieval ratio* as the ratio between the ideal traffic volume and the actual traffic volume generated during handover. The higher this value the higher data retrieval efficiency, and the less traffic generated. The ideal traffic here refers to data only travels along the shortest path between the consumer and producer. Results for this metric are given in Fig. 9, in which the Interest sending rate is set up 300 Interests per second. From the results, IIR-FH is the most efficient mechanism, with an average value over 90.9% with trivial deviations across different location combinations. IIR has an average value of 86.8% with small fluctuations across locations, between 82.1% and 92.5%. AIR performs the worst, with a value down to 68.1% for the New York consumer and the São Paulo producer. The results show that directing the retransmitted Interests to the previous access satellite using forwarding hints can effectively reduce the amount of additional traffic.

6 CONCLUSION AND FUTURE WORK

In this paper, we investigate applying NDN to large LEO satellite constellations. Specifically, we first discuss NDN's architectural benefits that can potentially provide a better solution in this scenario, including adaptive forwarding, in-network caching, off-the-grid communication, data mule service, in-network/edge computing, mobility support, and data-centric security. Then, we focus on studying NDN's consumer mobility support mechanisms, including Interest retransmission by applications, and in-network Interest retransmission. The performance of either mechanism depends on the retransmitted Interest routing path. With a real satellite constellation simulation, we observed that inter-orbital-plane routing uses a totally different path after a handover, hence underusing NDN's in-network caching. To address this issue, we intentionally direct retransmitted Interests due to satellite handovers to the previous connected

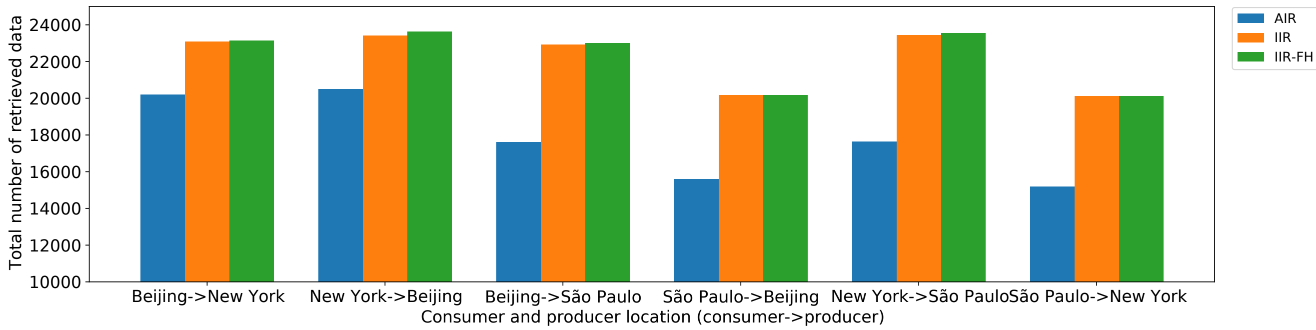


Figure 7: The number of the retrieved data vs. consumer and producer location

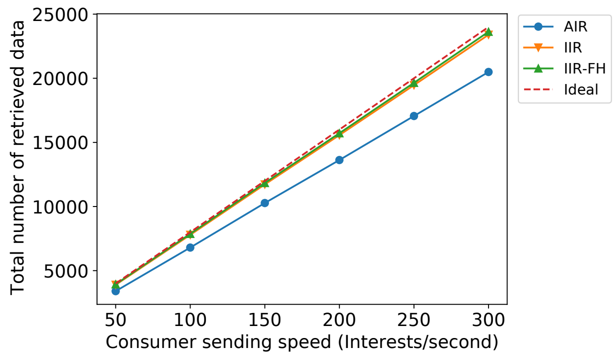


Figure 8: The number of retrieved data vs. consumer sending rates

satellite via forwarding hints. We implemented in-network Interest retransmission, and the one with forwarding hint in NFD, and simulated the aforementioned three approaches in ndnSIM. To simulate large LEO satellite constellations in ndnSIM, we implemented a simulation model to generate snapshots of satellites' positions given the settings of an existing large LEO satellite constellation. Simulation results show that directional routing with forwarding hint can improve in-network Interest retransmission, and both can decently improve the consumers' performance and reduce the network traffic, compared to NDN's native mobility support.

We consider this work to be the beginning of more significant work in this area. Regarding NDN's potential architectural benefits in this scenario, further investigation needs to be conducted, especially a comparison with IP-based architecture. Regarding NDN's consumer mobility support, our proposal uses forwarding hints to ensure NDN's symmetric routing in satellite handovers. Moreover, this approach can also be applied to nodes in the middle, e.g., satellites periodically connect to different inter-orbital-plane satellites. Additionally, it is potentially applicable to other MANET scenarios. Next, we recognize that the simulations are extremely limited and only provide a preliminary example. Various improvements can be added to the simulations in future work, such as more realistic constellation settings, comprehensive and realistic network traffic traces, etc. Last, producer mobility needs further investigation in this scenario.

7 ACKNOWLEDGMENTS

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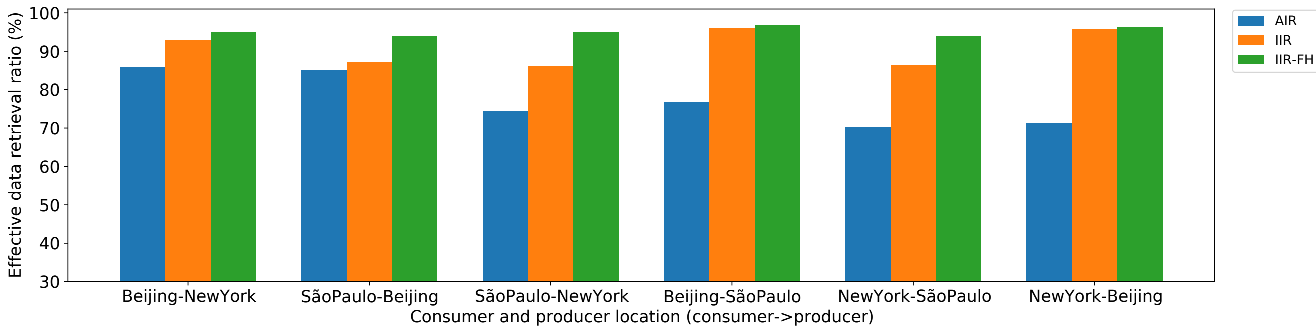

Figure 9: Effective data retrieval ratio vs. consumer and producer location

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