Analyzing Source-Routed Approaches for Low Earth Orbit Satellite Constellation Networks

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ABSTRACT

Source-routing is a commonly applied routing solution to space-based communication networks. Despite its simplicity and flexibility, the approach has known disadvantages like the creation of hot spots and inefficient link load acquisition. However, the actual performance of source-routing depends significantly on its specific implementation and the reference system. For this reason, we analyze the performance of different source-routing schemes in a realistic scenario using a system-level simulator. Most importantly, we want to quantify the impact of using the inherent path diversity of constellation networks with inter-satellite links more effectively. To this end, we compare the QoS compliance between a shortest-path-first path selection based on latency and a random path selection from a set of minimum hop routes. Additionally, we investigate the impact of uniform and population-based user terminal distributions.

CCS CONCEPTS

• **Networks → Network performance analysis**; *Network simulations*; Network control algorithms.

KEYWORDS

satellite constellation, routing, source-routing, performance

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1 INTRODUCTION

Low Earth Orbit (LEO) Satellite Constellation Network (SCN) have emerged as a promising solution to provide global broadband connectivity in recent years. Large LEO constellations using Intersatellite Links (ISLs) are garnering particular interest, with proposals to incorporate them into future terrestrial communication standards (e.g. beyond 5G and 6G) [7]. However, integrating this space network with a distributed ground segment is not a trivial task, in particular in the domain of routing [8]. Due to their distinct properties, SCNs require tailored routing solutions to enable the support of various Quality of Service (QoS) requirements [2]. So, in this paper we want to analyze the performance of one of the most common routing solutions for SCNs today: source-routed approaches. Furthermore, we want to investigate and quantify the impact of different scenarios and specific enhancements to such approaches. Source-routing is often utilized as a benchmark to compare the performance of newly proposed schemes (e.g. [15]). However, depending on the implementation of the source-routed scheme, varying performance can be observed. Moreover, the performance of source-routing also strongly depends on the envisioned traffic scenarios. For these reasons, an analysis of the impact of these factors in a realistic environment is required. In [10], the latency characteristics of source-routing are investigated. The work highlights that dense LEO constellations provide multiple paths of similar latency. Consequently, distributing flows over multiple paths can provide intrinsic load-balancing while upholding minimum latency requirements. We want to extend this analysis by comparing different path selection algorithms utilizing the described inherent path diversity and by comparing different User Terminal (UT) distributions (with a fixed Gateway station (GW) distribution). To this end, we simulate uniformly distributed UTs as well as UTs distributed based on population density. The analyzed source-routing schemes do not consider any link load information, as the acquisition of such information for each ingress node results in a significant amount of signalling traffic. Moreover, we want to measure the impact other drawbacks of such approaches. Namely, the additional operations required per hop and the impact of the additional processing delay.

The main contributions of this paper include:

- Practical enhancements and design choices based on the inherent structure of LEO satellite constellation networks are proposed for source-routed schemes. A comparative analysis is provided highlighting the impact of these adjustments. Additionally, the inherent disadvantages of source-routed approaches are quantified.
- The routing scheme, along with its variations, is implemented in a system-level simulator that enables per-packet analysis. The simulation environment facilitates comprehensive network assessments while taking into account constellation seams and inter-plane ISL shutdowns.

2 RELATED WORK

In order to provide increased autonomy and faster reactivity, many routing schemes with on-board decision making have been proposed for SCNs. There are two main approaches to handle the dynamicity of the network: based on a virtual topology or based on virtual nodes. Source-routing typically utilizes the former: paths are determined by an ingress node taking snapshots of the constellation. There are multiple examples for such approaches, which utilize protocols such as Asynchronous Transfer Mode (ATM) [17] or Multiprotocol Label Switching (MPLS) [5]. For SCNs, various source-routing approaches have been considered [10, 18]. The main issue with such source-routed schemes is the fact, that the decisions are made with limited information. So, in mesh networks with elevated traffic volumes, source-routed approaches are prone to hot spots [9]. For more flexible and scalable solutions, source-routing can be combined with Segment Routing (SR)[6] or distributed Software Defined Networking (SDN) for LEO SCNs [14, 15]. The idea is to provide distributed control, and local decision-making by the source node. These architectures and other approaches often utilize simple source-routing as a benchmark for performance evaluation. However, specifically tailored source-routed approaches can oftentimes deliver performance outcomes that are challenging to surpass with comparable efficiency and minimal signaling overhead.

3 REFERENCE SYSTEM

For this investigation, we will investigate a Walker star mega-constellation [16]. Due to the high Doppler in adjacent counter-rotating planes, we assume that no ISL connection is possible across these seams. We assume that each satellite has four optical ISLs: two intra-plane ISLs and two inter-plane ISLs. The constellation is constructed similarly to the constellation investigated in [15]. The parameters are listed in Tab. 1. Due to the relative speed and angle of satellites,

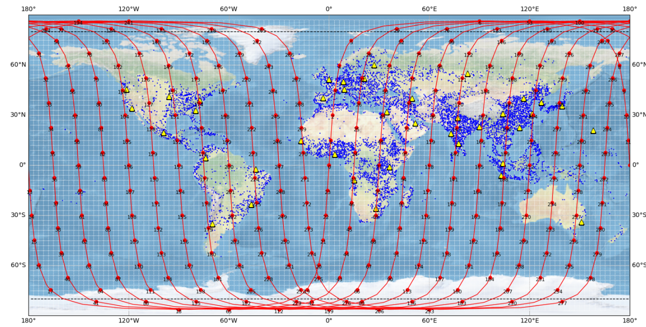

Figure 1: Reference system: P-288 constellation (red), user terminals (blue) and gateways (yellow) [13].

Table 1: Parameters of P-288 space & ground segment.

Space segment characteristic	Value
Number of satellites	288
Number of ISLs per satellite	4
Number of planes	12
Number of satellites per plane	24
Satellite altitude [km]	760
Orbital inclination [°]	86.4
Cross-seam planes spacing [°]	30
Co-rotating planes spacing [°]	15
Angular phase offset co-rotating planes [°]	7.5
Inter-plane ISL shut-down latitude [°]	80
ISL data rate [Mbps]	1000
On-board output buffer size [Mbit]	0.36
Aggregated maximum feeder downlink [Mbps]	5000
Aggregated maximum feeder uplink [Mbps]	5000
Ground segment characteristic	**Value**
Number of user terminals	2000
User terminal minimum elevation angle [°]	15
Number of gateway stations	39
Gateway minimum elevation angle [°]	10

inter-plane ISLs are typically deactivated to readjust - at a shutdown latitude of ±80°.

The ground segment of our reference system consists of UTs and GWs. The geographic distribution of the UTs is based on global population density statistics [3]. Their distribution is scaled to discount metropolitan and densely populated areas which tend to be well connected. The geographic distribution of the GWs is non-optimal and primarily based on existing Internet access infrastructure near cities. All elements of the reference system are shown in Fig. 1. We assume highly predictable seamless handovers for both ISLs and ESLs.

In real-world systems the interaction with higher layer protocols may also influence end-to-end performance, in particular for varying link capacities. Transport layer protocols such as TCP apply their own congestion mechanisms which can be counter-productive in an SCN scenario, depending on the applied routing solution. As we want to analyze source-routed schemes in isolation, such influences are not considered in this work. All links are assumed to maintain a constant capacity.

4 SOURCE-ROUTED APPROACHES

In the context of Low Earth Orbit (LEO) satellite constellation networks, source-routing presents a compelling routing strategy that capitalizes on its inherent flexibility, adaptability, and local decision-making advantages. As LEO constellations are characterized by dynamic and rapidly changing topologies, source-routing enables efficient route computation and selection by the source node (in our scenarios the ingress satellite) based on the network's current state. Since the acquisition of load information results in a massive amount of signalling overhead, we assume that no link load information is present at the ingress node. However, the orbits of the satellites are highly predictable, so the ISL connectivity and propagation delays can be computed at the source node (also in advance). A Shortest Path First (SPF) algorithm can then be utilized to find a path between the ingress satellite and the assumed egress satellite. If geographical addressing is used, the ingress node can compute which node should currently serve the destination. These computations can be done periodically according to a timed handover strategy. In our tests, we use an Multiprotocol Label Switching (MPLS)-like approach: the calculated path is added to the header of the packet and popped at every hop. The approach is considered viable, as MPLS-based schemes are employed in real-world satellite networking solutions [1].

For the path selection, SPF-algorithms like Dijkstra's algorithm [4] are commonly used. Shortest Path Trees (SPTs) can also be computed, comprising shortest paths to all vertices. Depending on the protocol setup, SPTs may be computed and stored periodically. Given link load estimates, constrained SPF algorithms are also possible, pruning links violating constraints (e.g. high ISL load). In the context of routing in large satellite constellations, it is important to mention that while the complexity of SPF algorithms is significant, they can be run efficiently on modern hardware - even with limited processing power [10].

4.1 Path selection

For source-routing, the path selection algorithm is crucial if we want to utilize the inherent path diversity of an SCN. By randomly choosing a path from the set of paths between the ingress and egress node, the load is intrinsically more balanced. This random path selection is flow-based in our analysis, to decrease jitter and the potential for packet reordering. Due to the grid structure of the mesh network, the set of minimum hop paths contains the fastest path in terms of propagation delay. As the paths of the minimum hop set have similar end-to-end propagation delay, they can be considered as viable alternatives. For the sake of simplicity, we focused on the minimum hop metric in this work. Nevertheless, it is possible to employ the propagation delay for path selection without significant processing overhead. The set of paths can be computed in a similar fashion based on the fastest path and an additional time threshold which maintains QoS compliance. Such a propagation delay-based approach may provide slightly improved performance compared to the minimum hop approach. Nevertheless, in tests, the resulting path sets were mostly identical.

Most importantly, it is possible to relax the minimum hop constraint (or propagation delay constraint), for instance by allowing paths with two or more additional hops. If the resulting end-to-end latency is compliant with the requirement of the QoS class, this relaxation can enable more intrinsic load-balancing. For the P-288 constellation, the intra-plane propagation delay is approximately $6ms$, and the maximum inter-plane propagation delay is approximately $8ms$. So, the maximum additional delay can be estimated easily based on the constellation design. In [2], the cost of additional hops and the relation to propagation delay is analyzed more thoroughly in a more flexible setting (the paper also considers adjustable ISLs between more distant satellites).

By applying heuristics, the paths can be found more efficiently. For instance, a bidirectional A* algorithm [11] can be used. However, due to the seams and the ISL inter-plane shutdown latitudes, a suitable distance metric is difficult to formulate. In our analysis, utilizing a Breadth-First Search (BFS) path discovery was efficient enough to compute all paths with the minimum amount of hops on an off-the-shelf laptop in milliseconds (as described in [10]).

While we focus on latency and packet dropping rate in this analysis, multiple relevant QoS metrics can complicate the problem. Linear, integer or dynamic programming techniques can then be applied and combined with source-routing. Alternatively, ML-based approaches have gathered interest, as they can approximate functions of optimization problems with lower computational complexity [19].

4.2 Signalling overhead

A common argument against source-routed schemes is the resulting signalling overhead. However, if the ISL and ESL connectivity is predictable, no signalling is required. The ingress nodes adjust their headers in time. As the route in

Table 2: Simulation parameters.

Simulation parameter	Value
Simulation duration [s]	7200
Number of sessions	$[30 \cdot 10^3, 120 \cdot 10^3]$
Average session duration [s]	100
Session data rate [Mbps]	10
Session begin distribution	uniform
Session duration distribution	normal
UT-GW (& vice-versa) traffic share	0.6
UT-UT traffic share	0.4
Packet size [kByte]	1.5
QoS latency requirement [ms]	< 150
QoS dropping rate requirement	$< 10^{-6}$

the header is typically not adjusted, there may be packets unable to reach their destination after a handover. Yet, this uncertainty in arrival times has negligible consequences for performance, as will be demonstrated. In general, the approach requires no periodic or load-triggered updates which is a significant advantage over most load-balancing schemes.

5 PERFORMANCE EVALUATION

In order to provide realistic results, a system-level simulator, which allows for packet-based analyses was used. The corresponding software is an extension of the simulative environment presented in [15]. The simulator was originally developed from scratch in C++. It employs a modular design, which makes use of templates to promote flexible adjustments and the potential for future enhancements. The simulator is based on an event loop of function calls, and allows for the individual analysis of simulated packets. Furthermore, it is equipped with timed handover events and signalling messages. The relevant simulation parameters are summarized in Tab. 2. The assumed QoS class characteristics are included. The simulated traffic consists of individual sessions between randomly chosen terminals on ground with constant data rates. In a first test, we want to illustrate the tendency of source-routing to create bottlenecks. To this end, we compare the shown density-based UT distribution with a uniform UT distribution (in both cases 2000 active UTs). It is important to note, that 60% of traffic is still UT-to-GW and vice-versa. Since the GWs maintain their positions, links in their proximity remain potential hot spots.

The UT-to-UT traffic share assumption of 40% results in a more diverse ingress and egress node distribution. This facilitates a more comprehensive evaluation of the load-balancing capacities of the approaches. If we consider significantly higher UT-to-GW and vice-versa traffic share (e.g., more streaming-related traffic), last-hop ISLs as well as the ESLs of GWs are the most likely bottlenecks. Depending on the ESL connectivity, routing solutions may not be able to avoid such bottlenecks at the egress node. Instead, additional ESLs to other satellites or higher ESL data rates are required in this case.

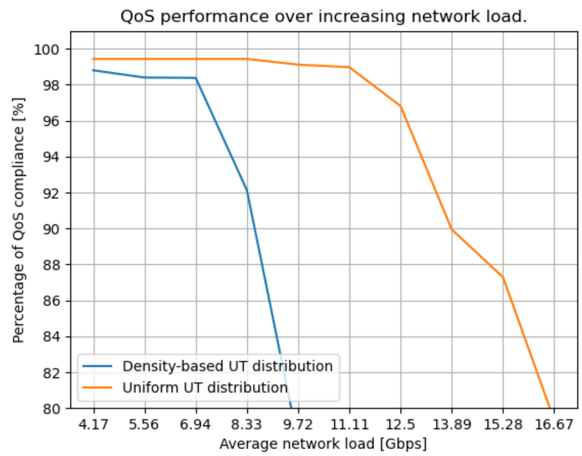

Figure 2: UT distribution impact on QoS performances for increasing network loads.

Fig. 2 illustrates that the non-uniformly distributed traffic requirements cause the source-route approach to be more susceptible to hot spots. Indeed, the sessions are non-compliant due to the increased packet dropping rates at higher network loads. A drop occurs if a packet cannot be queued in the corresponding output buffer of the satellite. Either because the buffer is currently at maximum capacity or because the next hop defined in the header no longer exists due to a handover. Using Little's law [12], we can estimate that there is an average network load of $9.72 Gbps$ for 70000 sessions and $16.67 Gbps$ for 120000 sessions. These values correspond to the average network load measured during the simulation. As expected, the inherently more diverse routes for a uniform UT distribution enable higher loads. We can support approximately 64% more traffic (QoS compliance > 95%).

Fig. 3 shows the chosen paths for the density-based UT distribution. The movement of the satellites causes frequently chosen routes to appear thicker. Although it is obvious that certain paths are more commonly used than others, the route diversity is still remarkable. Mostly paths across the Pacific ocean are favored less, due to their unattractive delay characteristics.

Next, we want to evaluate the performance enhancements of using random paths with an equal number of hops based on the minimum hop metric. The results of Fig. 4 illustrate the performance improvements of the enhanced approach. By using a minimum hop metric instead of the propagation

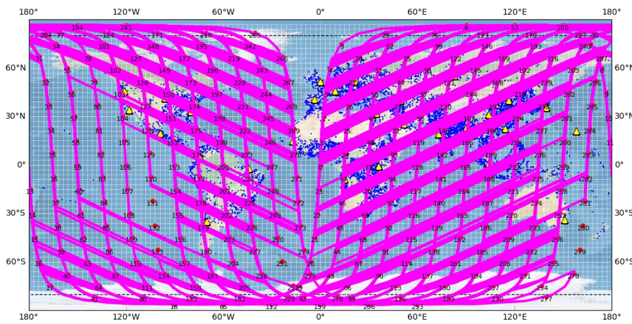

Figure 3: Distribution of paths over time: utilized ISLs.

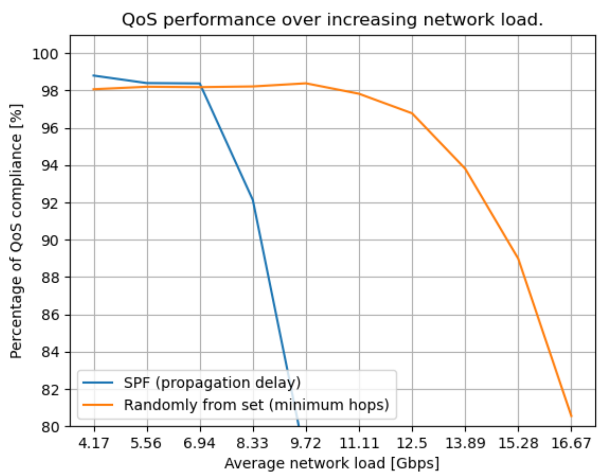

Figure 4: Path selection impact on QoS performances for increasing network loads (population-based UTs).

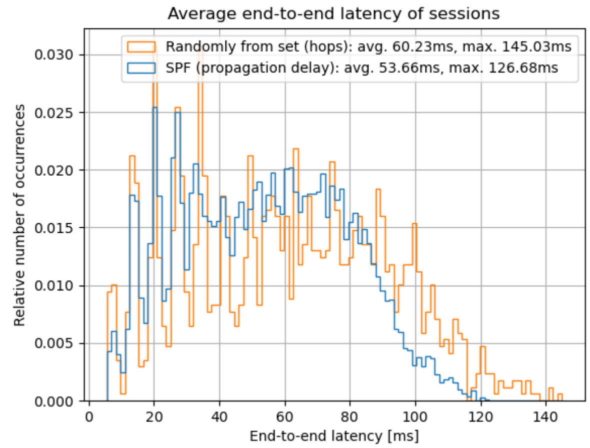

Figure 5: Path selection impact on session-based end-to-end latency (population-based UTs).

delay, and applying a random path selection per flow, we reduce the tendency for hot spots. Approximately 73% more traffic can be supported (QoS compliance $> 95\%$). The inherent route diversity of the SCN is used more effectively - without considering load information at the source node at all.

Looking at the end-to-end latency depicted in Fig. 5, we see that both approaches perform as anticipated, with the propagation delay-based SPF offering superior performance (on average 53.66ms). Despite being marginally less efficient, the enhanced scheme still achieves comparable performance (on average 60.23ms). Therefore it should be the preferred option, unless latency has to remain as minimal as possible.

The drawbacks of source-routing were quantified as well. While we applied the processing penalty on each hop, its effect on the average end-to-end latency was not significant. We assumed a processing time of 50μs for each packet processing operation. So, even if consider longer routes consisting of 20 hops, only an additional delay of 0.55ms is observed. On the other hand, the amount of additional header operations increased linearly with the number of forwarded packets. At $3.5 \cdot 10^6$ packets, approximately $30.0 \cdot 10^6$ additional operations were required. So, around 8.6 header label operations per packet. Signalling messages and the resulting overhead are simulated as well. However, due to the described predictable handover strategies, no dedicated signalling is required for the source-routing approach. For decentralized approaches, unpredictable topology changes have to be broadcast to all nodes. This includes scenarios with mobile UTs or satellite failures. However, in all test cases, the relative share of signalling overhead was below 1% of the overall traffic.

5.1 Discussion and Limitations

In summary, the results reflect the initial intuitive expectations. Nevertheless, for large constellation networks with multiple routes of similar end-to-end propagation delay, the effective increase in supported network load is quite significant. The results provide quantitative evidence of the effectiveness of employing spreading mechanisms in source-routed approaches, which explains why they are viewed as candidate solutions for SCNs.

Since similar schemes have been used effectively for Walker delta constellations [10], the presented analysis and comparison focused on Walker star constellations. In general, the presented approaches and adjustments are viable for both patterns. Due to the seams of Walker star constellations, completely different paths have to be taken after an ESL handover there. So, tailoring the routing solution to the handover scheme is particularly important in this context.

In the proposed approach, load information is not used, leading to a path distribution that differs from active load-balancing. Sharing all link load details for every possible entry satellite is considered too expensive given the unpredictable traffic characteristics and the network topology. The physical size of these networks also leads to notable delays, limiting reactive load-balancing schemes. Therefore, the principal advantage of the approach is that it utilizes the path diversity of the network without extra signalling overhead. Comparisons to dedicated load-balancing schemes were omitted due to the scope of the investigation. However, simple SPF source-routed schemes are oftentimes used to evaluate the performance of load-balancing algorithms. Thus, comparisons in terms of estimated performance are possible in an SCN context.

6 CONCLUSION

In this paper, we have demonstrated on a system-level basis why source-routed approaches remain an attractive option for LEO satellite constellation networks, offering flexibility and adaptability to various network scenarios. By employing a random choice for new flows from a set of minimum hop (or minimum delay) paths, the inherent route diversity of the network is used more effectively, enabling higher traffic loads without additional signalling and synchronization overhead. Future research should consider the trade-offs between such enhanced source-routing and other routing approaches on a practical level, as well as its combination with different architectures and heuristics.

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