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## **Problems and Requirements of Evaluation Methodology for Integrated Space and Terrestrial Networks**

### **Abstract**

With the rapid evolution of the aerospace industry, many "NewSpace" upstarts are actively deploying their mega-constellations in low earth orbits (LEO) and building integrated space and terrestrial networks (ISTN), promising to provide pervasive, low-latency, and high-throughput Internet service globally. Due to the high manufacturing, launching, and updating cost of LEO mega-constellations, it is expected that ISTNs can be well designed and evaluated before the launch of satellites. However, the progress of designing, assessing, and understanding new network functionalities and protocols for futuristic ISTNs faces a substantial obstacle: lack of standardized evaluation methodology with acceptable realism (e.g. can involve the unique dynamic behaviors of ISTNs), flexibility, and cost. This memo first reviews the unique characteristics of LEO mega-constellations. Further, it analyzes the limitation of existing evaluation and analysis methodologies under ISTN environments. Finally, it outlines the key requirements of future evaluation methodology tailored for ISTNs.

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## 1. Introduction

Integrated Space and Terrestrial Networks (ISTN), combining diverse spacecrafts and ground infrastructures, are extending the frontier of today's terrestrial network, promising to provide low-latency, high-bandwidth Internet access with broader coverage globally.

Low earth orbit (LEO) satellites are the key building block for constructing ISTNs. Recently, we have witnessed a renaissance in the space industry, stimulating an exponential increase in constructing mega-constellations. As compared with their predecessor, cutting-edge satellites can be equipped with high-resolution sensors, space-grade multi-core processors, high-data-rate communication links, and multifunctional space software.

While ISTNs hold great promise, to completely unleash the network potential of emerging ISTN, it still needs to address a series of new technical issues. The unique characteristics of LEO satellites (e.g., high-dynamics), not only impose new challenges at various layers of the ISTN networking stack but also open the door to many new technical problems. With many unexplored problems facing the "NewSpace" industry, it is thus foreseen that in the near future, there will be a surge of new efforts (e.g. topology, addressing, routing, transport, etc.) to rethink and reshape the networking stack in ISTNs. In addition, the cost/timeline of manufacturing, launching, operating, and updating satellite constellations is typically much higher/longer than that in traditional terrestrial networks. Therefore, it is expected that new network functionalities and protocols can be well evaluated before they are launched and deployed in realistic satellite constellations.

However, the network community lacks the proper analysis tools and evaluation methodologies that can mimic the unique dynamic behavior to analyze many of the ISTN challenges that have been highlighted by prior works. At high level, existing evaluation methodologies in the network community can typically be grouped into three major categories: live networks or platforms, simulation, and emulation. However, the feasibility and flexibility of live satellite networks are technically and economically limited. The abstraction level of network simulation could be too high to capture low-level system effects. Existing network emulators fail to characterize the high dynamicity of LEO satellites and thus cannot accomplish an environment with acceptable fidelity. The community hence needs a reasonable and standardized evaluation methodology to build proper experimental environments which can mimic the behavior of ISTNs, supporting the community to deeply understand the problems, and to evaluate new functionalities and protocols (e.g. for topology, addressing, routing, transport, etc.) for ISTNs, before the mega-constellation is completely deployed. In this memo, we first review

the unique characteristics of emerging LEO mega-constellations and the key challenges of integrating satellites and terrestrial Internet. Further, we analyze the limitation of existing network analysis tools and evaluation methodologies in ISTNs. Finally, we outline key requirements of evaluation methodologies tailored for ISTNs.

## 2. Notation and Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC 2119](#) [[RFC2119](#)].

This document uses the following acronyms and terminologies:

Mega-constellation: A group of satellites working as a system.

LEO: Low Earth Orbit with an altitude no more than 2000 km.

MEO: Medium Earth Orbit with an altitude from 2000 km to 35786 km.

GEO: Geostationary Earth Orbit with an altitude of 35786 km.

NGSO: Non-Geostationary Orbit

LSN: LEO Satellite Networks

ISTN: Integrated Satellite and Terrestrial Network

ISL: Inter-satellite Links

EO: Earth Observation

GS: Ground Station

AS: Autonomous System

EOS: Earth Observation Satellite

BGP: [Border Gateway Protocol](#) [[RFC4271](#)]

OSPF: [Open Shortest Path First](#) [[RFC2328](#)]

VM: Virtual Machine

## 3. Quick Primer for Integrated Space and Terrestrial Networks

Emerging mega-constellations with inter-satellite links (ISLs) can build a satellite network in outer space, and further be integrated with terrestrial ground infrastructures to construct an integrated space and terrestrial network (ISTN).

### 3.1. Mega-constellation

A constellation is a group of satellites working as a system to give a coverage of the earth surface, among which satellites are positioned in fixed orbital planes with regular trajectories. LEO and MEO satellites often belong to a constellation, because a single satellite only covers a small area with high angular velocity. Thus, continuous coverage over an area could be maintained by the relay within a constellation, as compared with GEO satellites that only provides a permanent coverage over a target area. Walker Delta constellation is the most common formation for constellations. It is defined as a bunch of circular orbits with a fixed inclination, satellite number, number of equally spaced planes and the relative spacing between satellites in adjacent planes. The famous Ballard rosette constellation is another name of Walker Delta constellation, where it uses a different notation. Near-polar Walker Star is one of this kind, initially used by [Iridium](#) [[Iridium](#)]. Constellations with a higher inclination give the polar regions more chances to get accessed. The well-known emerging commercial constellations are [Starlink](#) [[Starlink-Fcc](#)], [Kuiper](#) [[Kuiper-Fcc](#)] and [Telesat](#) [[Telesat-Fcc](#)], as shown in [Table 1](#) below. And all of them contain more than one shell.

Name and Shell	Altitude (km)	Inclination (degree)	# of orbits	# of satellites per orbit
Starlink S1	550	53	72	22
Starlink S2	1110	53.8	32	50
Starlink S3	1130	74	8	50
Starlink S4	1275	81	5	75
Starlink S5	1325	70	6	75
Kuiper K1	630	51.9	34	34
Kuiper K2	610	42	36	36
Kuiper K3	590	33	28	28
Telesat T1	1015	98.98	27	13
Telesat T2	1325	50.88	40	33

Table 1: Mega-constellation information.

### 3.2. Topological Dynamics

Unlike geostationary satellite networks or terrestrial core infrastructure that keep a stable topology, LEO satellite networks suffer from high topological dynamics, since LEO satellites move fast, causing short-lived coverage for fixed terrestrial users. For

example, considering the first shell of Starlink Phase-I, a fixed user sees each satellite for only up to 3 minutes in one pass, after which the satellite moves away from the user's perspective. [Table 2](#) shows the medium space-ground [link churn intervals](#) [[link-churn-interval](#)] between existing GS and constellations. If each GS only uses one antenna to connect the satellite with the shortest distance, the medium interval is no more than one minute. This kind of high dynamic motion incurs frequent link changes between LEO satellites and GS or users, thus causing frequent topology changes. Moreover, inter-satellites visibility may also change if LEO satellites move in different directions or in different shells, resulting in connectivity change of ISLs.

Such high LEO dynamics can impose significant challenges in the networking stack of ISTNs. The high dynamics make the logical network and mega-constellations and physical ISTN inconsistent. One big challenge is how to overcome the routing oscillation properly in the high dynamic ISTN environment. Frequent satellite-GS link changes make the inter-connectivity of space and ground segments in ISTNs unstable. Thus, the routing have to be re-calculated every time the link changes. In addition, the topological dynamics also result in RTT fluctuations in end-to-end paths, involving new challenges for congestion control in ISTNs, as a RTT variation observed by end-host might not indicate congestions.

Name	Interval (s)
Starlink	3.0901
Kuiper	5.0562
OneWeb	10.6824
Telesat	45.5696

Table 2: Space-ground link churn interval.

### 3.3. Limited Resources

Space resources (e.g. CPU, energy) on satellites are limited, as compared with terrestrial network. Since resource-constrained satellites such as nanosatellites are only able to carry certain sensing or transferring missions, energy-consuming or complex tasks may not be achievable in these satellites. Such complicated tasks include on-board target identification and instant and continuous disaster monitoring.

For example, the CPU frequency of current spaceborne processors (e.g. [RAD5545](#) [[RAD5545](#)], [RAD750](#) [[RAD750](#)]) is only up to 466MHz per core. More recently, [some low energy-consuming commodity processors are used in space to complete certain remote sensing missions under a limited CPU capacity.](#) [[raspberry-pi](#)] With a constrained

computation ability and limited storage and energy, satellite functions and lifetime are greatly repressed.

### **3.4. Long Manufacturing and Deployment Duration**

Different from terrestrial network infrastructures, the timeline of manufacturing and deploying satellite networks could be much longer due to the high cost and complex process during the development and launch period. Satellites, as well as the orbit and spectrum they used, have to be regulated, and launches have to be carefully scheduled (e.g. to avoid the impact of poor weather conditions). In addition, the maintenance and update cost of a satellite network is also typically much higher than that in a terrestrial network.

[For example, a review of 24 Air Force and Navy space vehicle \(SV\) development programs found that on average it took about 7.5 years from contract start to launch a government satellite. \[Development-Timeline\]](#) [Commercial satellite programs typically take 2 to 3 years from contract start to launch. \[Production-Cycles\]](#) SpaceX's Starlink constellation plan to launch about 42,000 satellites to construct a mega-constellation in outer space. On 15 October 2019, the United States Federal Communications Commission (FCC) submitted filings to the International Telecommunication Union (ITU) on SpaceX's behalf to arrange spectrum for 30,000 additional Starlink satellites to supplement the 12,000 Starlink satellites already approved by the FCC. As of the date of April 2022, SpaceX has launched about 2,100 Starlink satellites, which is about 5% of the ultimate constellation plan consisting of 42,000 satellites. Foreseeably, it may take many years to complete the entire constellation deployment. Even the first phase of Starlink which consists of about 4400 satellites is not expected to be completed until 2024.

## **4. Problem Statement: We Need the Right Evaluation Methodology**

The unique characteristics of LEO mega-constellations involve new challenges on various layers of the networking stack of ISTNs. On one hand, it is foreseen that in the near future, there will be a surge of new network functionalities and protocols designed or optimized for ISTNs. On the other hand, because the cost/timeline of manufacturing, launching, operating, and updating satellite constellations is typically much higher/longer than that in traditional terrestrial networks, it is expected that those new network functionalities and protocols tailored for ISTNs should be well evaluated before they are launched and deployed in realistic satellite constellations.

Existing methodologies for testing, assessing, and understanding a network functionality or protocol can typically be classified into three categories: (1) live networks; (2) network simulators; and (3)

network emulators. The subsections discuss these three categories of network evaluation methodologies, along with their using deficiencies and possible remedies respectively.

#### **4.1. Live networks and platforms**

Representative platforms such as [Emulab](#) [Emulab] and [Sparta](#) [Sparta] are successful pioneers that build a large-scale experimental network environment. These test environments are originally designed to provide special and exclusive test services for affiliated universities, scientific research institutions or Internet business companies. And for the resource competition, each independent experiment needs to completely monopolize a part of the test bed, so the researcher cannot deploy the experiment until being allocated with enough nodes. [PlanetLab](#) [PlanetLab] is truly global ground testbed prototype. Started from 2003, it consists of 1353 nodes at 717 sites spanning 48 countries. Together the nodes form a global network system to support new design of network services.

The live platforms described above were initially proposed for terrestrial networks and they are developed and repaired at the same time. The key limitation of them in an ISTN environment is that they are designed for terrestrial network experiments, and do not incorporate the realistic characteristic of LEO mega-constellations to support experiments and evaluations in ISTNs.

We may search for help from live satellites, but still there is only limited help. It seems that with the help of live ISTN, researchers are capable to assess, verify and evaluate their ideas and thoughts. Live ISTN can give a real constellation-consistency and stack-consistency testing environment. However, current satellites only provide users a bent-pipe service, which is purely relaying the transmission messages, such as the current deployment of [Starlink](#) [Starlink]. The construction is far from a comprehensive ISTN, so the research scope is limited. Even if there is a live ISTN, it lacks flexibility, owing to the inconvenient control over satellites. Besides, the access to satellites is also limited.

Therefore, live networks or platforms for terrestrial networks can give us a large-scale experimental environment but they lack the support for ISTN characteristics. On the other hand, live ISTN is able to guarantee a real space environment, but it is not that affordable and flexible.

#### **4.2. Network Simulators**

Simulators are tools that enable researchers to reproduce their testing experiments by simulating a real-world process or system over time. Simulators work by using discrete event simulation to



calculate the interactive states among all the network entities, ranging from switches, routers, nodes, access points, links and so on. While working fast and efficiently, the fidelity is only brought by the state variable changes at discrete points.

Such tools like [Systems Tool Kit \(STK\)](#) [[Systems-Tool-Kit](#)] and [General Mission Analysis Tool \(GMAT\)](#) [[General-Mission-Analysis-Tool](#)] are good for orbit analysis. STK is a powerful tool to help researchers to model the behavior of mission entities in aerospace, telecommunications and so forth. It also provides visualization and analysis functions. GMAT is a similar tool for space trajectory optimization and mission modeling. Nevertheless, these tools do not support networking simulations such as topology and protocol simulations. [ns-3](#) [[ns-3](#)] goes a step further with support for Internet simulation, but on the contrary, it was not designed for ISTN and lacks the support for high-dynamics of ISTN. [StarPerf](#) [[StarPerf](#)] is a simulator that helps researchers to study network performance under a range of constellation conditions. But still, it lacks the ability to support interactive network traffic simulation and system codes in the systems.

Overall, while flexible and low-cost, the realism of simulators is not content enough, because they are difficult to describe the low-level characteristics. In other words, simulators are being too object-oriented to involve additional overhead in the actual execution of programs. Besides, when accessing the network performance, a number of recent emerging algorithms for congestion control, reliable transmission or even protocols are not supported, for example [ns-3](#) [[ns-3](#)] only supports basic congestion control like [Reno](#) [[RFC6582](#)] and so forth, so the need to work with some new algorithms cannot be satisfied and the research to discover new mechanisms, such as new routing algorithms and re-transmission schemes, is extensively prohibited. Another problem of simulators, such as [ns-3](#) [[ns-3](#)], is that it difficult to trace or understand the previous codes, without appropriate documentations. Simulators usually face the additional compatibility problem, which means they are not portable with other systems, or they do not support kernel codes. Since there are multiple simulators developed by different group of users, sometimes users are required to be familiar with the writing language, scripting style and modelling technique.

#### **4.3. Network Emulators**

Emulators are another kind of paradigm for network evaluation over a virtual network. The difference between a simulator and an emulator is that emulators leverage VM or containers to keep the realism which is close to actual performances. Therefore, in emulators, virtual nodes, virtual network links, virtual models of traffic, and protocols are all applied. Emulators are capable to run real kernel

and application code. Thus, emulators not only support diverse topology design, but also protocol emulation in a synthetic network environment. They emulate the network behavior in a more real way. [Mininet](#) [[Mininet](#)] is commonly regarded as the most illustrious emulator for networking with its strong ability to support experiments with [Software-Defined Networking \(SDN\)](#) [[Software-defined-networking](#)] systems. [EstiNet](#) [[EstiNet](#)] is another emulator that supports evaluating and testing the performances of software-defined networks. Based on containers, they can emulate real TCP/IP protocol stack in the Linux kernel. However, existing emulation tools lack the ability to construct the dynamic links and orbits in ISTN like simulators. Thus, more problems could happen in higher-level protocols such as routing protocols (e.g. OSPF and BGP). Besides, since emulators run containers or virtual machines which occupy more software overhead, as compared with simulators, it will be hard to emulate the large-scale mega-constellations.

To conclude, emulators are relatively good methodologies for network experiments, but emulators still have limitations when using them for ISTN research. While keeping a moderate realism by using VM or containers for entity emulation and flexibility, emulators still lack the supports for ISTN characteristics, such as frequent link changes, satellite network topology uncertainty, and so on. More specifically, current emulators only support fixed network topology emulation. It is not flexible to emulate the time-varying link packet loss, bandwidth, and other traits. A possible way is to frequently replace the link with a new one from time to time sequentially for the entire ISTN. However, it is far from the real situation. Besides, VM or containers are able to deploy a range of network nodes in a physical server, but the actual CPU, memory and other resources should not be shared in reality for each satellite. In addition, it is still difficult to emulate thousands or ten thousand of satellites for ISTN even with VM or containers, subject to hardware limitations. For flexibility, some emulators do not support a good network animator tool. Especially in ISTN emulation, GUI is important for users to observe and analyze orbit trajectories and real time satellite positions.

#### 4.4. Summary

In this section, we explain the necessity of an evaluation methodology specifically for ISTNs. Then we demonstrate the problems with existing methodologies related to ISTNs. The performance comparison result is shown in [Table 3](#). Above all, ISTNs should be designed first and then launched. Live satellites enable good realism but they lack flexibility and require very high cost as well as a very long deployment period. Other testing tools such as simulators and emulators are either functional for merely aerospace analysis or simply terrestrial networks. None of the existing

methodologies guarantees a practical and user-friendly methodology while keeping the evaluation environment realism with low costs.

Platform/Tool	Realism	Flexibility	Cost	Cross-domain Dataset Support
Live satellite network	Y	N	High	Y
<a href="#">ns-3</a> [ <a href="#">ns-3</a> ]	N	Y	Low	N
<a href="#">Hypatia</a> [ <a href="#">Hypatia</a> ]	N	Y	Low	N
<a href="#">StarPerf</a> [ <a href="#">StarPerf</a> ]	N	Y	Low	N
<a href="#">Mininet</a> [ <a href="#">Mininet</a> ]	N	Y	Low	N

Table 3: Existing platforms/tools for network analysis and evaluation.  
(Y for yes/N for no)

## 5. Requirements: New Evaluation Methodology Tailored for ISTNs

A proper evaluation methodology tailored for ISTNs is expected to help developers, researchers, engineers to explore various design-space of the networking stack of ISTNs in a technically and economically feasible manner. Based on the comparative analysis results in the prior section, we sum up the following requirements for the new evaluation methodology in ISTNs.

### 5.1. Realism

The first requirement is realism. Realism represents the testing authenticity and fidelity. The evaluation methodology is expected to keep the actual characteristics of mega-constellations. In other words, the orbit-level information including the latitude, longitude, and height of each satellite in any given time and the same information for GS and elevation angles of antennas of each GS. Note that the constellation information also determines the visibility, links and even topology of ISTN.s Since the mega-constellations are unstable, how the temporal satellite locations, visibility, link propagation delays and so on should also be considered carefully. In addition, it requires the network nodes to communicate and negotiate their messages following the actual protocol process. For example, when doing a test for OSPF in an ISTN, we would like the nodes to send Hello packets, Link-State-Request (LSR) packets, Link-State-Update (LSU) packets and so on. A real network stack is preferred to provide researchers an opportunity to see the performance of different protocols in ISTNs.

### 5.2. Flexibility

Another requirement is flexibility and feasibility. The testing methodology should be technically easy to use and easy to learn.

Without extra modifications or process, the methodology should help researchers learn and use it without much effort and can evaluate their ideas as they wish, which means it should support flexible, controllable environments for researchers.

### **5.3. Low-cost and Easy-to-use**

Meanwhile, the evaluation methodology is expected to be low-cost. A well-acceptable methodology should be economically feasible for users to create an evaluation environment. Researchers do not want to conduct their tests all in live ISTN, which is over-cumbersome and unaffordable, let alone launching their own spacecraft. Even if there are a number of orbiting satellites, whether users can easily gain access to satellites is also a problem.

### **5.4. Cross-domain Dataset Support**

The evaluation methodology is expected to be driven by realistic datasets from multi-dimensions to support its realism. Multi-dimension refers to multi-disciplinary research on ISTNs. Since a standard ISTN evaluation methodology not only contains high-level benchmarks from topology, routing to transmission, but also considers the low-level traits such as wireless link conditions, weather conditions and Earth rotations. To be more concrete, the former one requires knowledge in networks while the latter one relies more on aerospace. Hence, to build a high-fidelity methodology, we need community efforts both from networks and aerospace. On the other hand, an authentic dataset is an indispensable element for data driven testing methodology. Actual data is the first step to obtain a realistic emulation. with characteristics of a real ISTN. Thus, the dataset is a collection of messages for testing, in which geographical mega-constellation information (orbit number, satellite number, height), orbital information (orbit inclination angle and link strategies), weather information as well as ground station information (positions, antenna angle and so forth) are involved.

## **6. Conclusion**

To conclude, the emergence of mega-constellations brings us new opportunities for the development of ISTN that extends the Internet to the space era. Combined with terrestrial networks, ISTN is expected to supply pervasive, low-latency and high-speed services to users globally, which greatly enhances the current Internet. At the same time, the unique characteristics (e.g. high-dynamics) of ISTN impose challenges in topology, routing, transportation, application, and security. However, we simply believe addressing the challenges also gives us open opportunities for future research by our community-driven effort. To accelerate the research speed and to

help make testing more feasible, new methodologies that satisfy user requirements should be proposed. To this extent, this draft reviews the limitation of existing network analysis tools in ISTNs, considering the unique characteristics of emerging LSNs and the key challenges. This draft further analyzes the limitation of existing evaluation methodologies in ISTN environments. Finally, this draft outlines key requirements of evaluation methodologies tailored for future ISTNs.

## **7. Acknowledgements**

## **8. IANA Considerations**

This memo includes no request to IANA.

## **9. Security Considerations**

This entire draft discusses security considerations from different perspectives of ISTN in Section 3.

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