Workgroup: Network Working Group
Internet-Draft:
draft-lhan-problems-requirements-satellite-net-04
Published: 4 January 2023
Intended Status: Informational
Expires: 8 July 2023
Authors: L. Han, Ed.
Futurewei Technologies, Inc.
R. Li
Futurewei Technologies, Inc.
A. Retana
Futurewei Technologies, Inc.
M. Chen
China Mobile
L. Su
China Mobile
Tianji. Jiang
China Mobile
N. Wang
University of Surrey

Problems and Requirements of Satellite Constellation for Internet

Abstract

This document presents the detailed analysis about the problems and requirements of satellite constellation used for Internet. It starts from the satellite orbit basics, coverage calculation, then it estimates the time constraints for the communications between satellite and ground-station, also between satellites. How to use satellite constellation for Internet is discussed in detail including the satellite relay and satellite networking. The problems and requirements of using traditional network technology for satellite network integrating with Internet are finally outlined.

Status of This Memo

Copyright Notice

Table of Contents

1. Introduction

Satellite constellation for Internet is emerging. Even there is no constellation network established completely yet at the time of the publishing of the draft (June 2021), some basic internet service has been provided and has demonstrated competitive quality to traditional broadband service.

This memo will analyze the challenges for satellite network used in Internet by traditional routing and switching technologies. It is based on the analysis of the dynamic characters of both ground-station-to-satellite and inter-satellite communications and its impact to satellite constellation networking.

The memo also provides visions for the future solution, such as in routing and forwarding.

The memo focuses on the topics about how the satellite network can work with Internet. It does not focus on physical layer technologies (wireless, spectrum, laser, mobility, etc.) for satellite communication.

2. Terminology

LEO Low Earth Orbit with the altitude from 180 km to 2000 km.

VLEO Very Low Earth Orbit with the altitude below 450 km

MEO Medium Earth Orbit with the altitude from 2000 km to 35786 km

GEO Geosynchronous orbit with the altitude 35786 km

GSO Geosynchronous satellite on GEO

ISL Inter Satellite Link

ISLL Inter Satellite Laser Link

3GPP 3rd Generation Partner-ship Project

NTN Non-Terrestrial Network, it includes satellite networks (satellite could be on GEO, MEO, LEO or VLEO), high altitude platform systems (HAPS) and other types of air-to-ground networks

EIRP Effective isotropic radiated power

P2MP Point to Multiple Points

GS Ground Station, a device on ground connecting the satellite. In the document, GS will hypothetically provide L2 and/or L3 functionality in addition to process/send/receive radio wave. It might be different as the reality that the device to process/send/receive radio wave and the device to provide L2 and/or L3 functionality could be separated.

SGS Source ground station. For a specified flow, a ground station that will send data to a satellite through its uplink.

DGS Destination ground station. For a specified flow, a ground station that is connected to a local network or Internet, it will receive data from a satellite through its downlink and then forward to a local network or Internet.

PGW Packet Gateway

UPF User Packet Function

NodeB The base station in 3G

eNodeB The base station in 4G

gNB gNodeB, the base station in 5G

PE router
Provider Edge router

CE router Customer Edge router

P router Provider router

LSA Link-state advertisement

LSP Link-State PDUs

L1 Layer 1, or Physical Layer in OSI model [OSI-Model]

L2 Layer 2, or Data Link Layer in OSI model [OSI-Model]

L3 Layer 3, or Network Layer in OSI model [OSI-Model], it is also called IP layer in TCP/IP model

BGP Border Gateway Protocol [RFC4271]

eBGP External Border Gateway Protocol, two BGP peers have different Autonomous Number

iBGP Internal Border Gateway Protocol, two BGP peers have same Autonomous Number

IGP Interior gateway protocol, examples of IGPs include Open Shortest Path First (OSPF [RFC2328]), Routing Information Protocol (RIP [RFC2453]), Intermediate System to Intermediate System (IS-IS [RFC7142]) and Enhanced Interior Gateway Routing Protocol (EIGRP [RFC7868]).

3. Overview

The traditional satellite communication system is composed of few GSO and ground stations. For this system, each GSO can cover 42% Earth's surface [GEO-Coverage], so as few as three GSO can provide the global coverage theoretically. With so huge coverage, GSO only needs to amplify signals received from uplink of one ground station and relay to the downlink of another ground station. There is no inter-satellite communications needed. Also, since the GSO is stationary to the ground station, there is no mobility issue involved.

Recently, more and more LEO and VLEO satellites have been launched, they attract attentions due to their advantages over GSO and MEO in terms of higher bandwidth, lower cost in satellite, launching, ground station, etc. Some organizations [ITU-6G][Surrey-6G] [Nttdocomo-6G] have proposed the non-terrestrial network using LEO, VLEO as important parts for 6G to extend the coverage of Internet.

3GPP has been working on the NTN integration with 5G and beyond. SpaceX has started to build the satellite constellation called StarLink that will deploy over 10 thousand LEO and VLEO satellites finally [StarLink]. China also started to request the spectrum from ITU to establish a constellation that has 12992 satellites [China-constellation]. European Space Agency (ESA) has proposed "Fiber in the sky" initiative to connect satellites with fiber network on Earth [ESA-HydRON].

When satellites on MEO, LEO and VLEO are deployed, the communication problem becomes more complicated than for GSO satellites. This is because the altitude of MEO/LEO/VLEO satellites are much lower. As a result, the coverage of each satellite is much smaller than for GSO, and the satellite is moving very fast on the ground reference and not relatively stationary to the ground. This will lead to:

1. More satellites than GSO are needed to provide the global coverage. Appendix A will brief the satellite orbit parameters; analyze the coverage area, and the minimum number of satellites required to cover the earth surface; discuss the real deployment for LEO satellite network.

2. The point-to-point communication between satellite and ground station can only last a few minutes. Mobility issue has to be considered. Detailed analysis about the lifetime of communication is done in Appendix B.1.

3. The inter-satellite communication is needed, and all satellites need to form a network. details are described in Appendix B.2 that includes the communication between satellites on different orbit and different geographic areas.

In Section 4, we will discuss couple of topics of satellite network integration with Internet, such as using satellite network for broadband access and wireless access, the current 3GPP works for satellite network in 5G and beyond.

Finally, the problems and requirements for satellite network integration with Internet will be discussed and analyzed in Section 5.

As the 1st satellite constellation company in history, the SpaceX/StarLink will be inevitably mentioned in the draft. But it must be noted that all information about SpaceX/StarLink in the draft are from the public. Authors of the draft have no relationship or relevant inside knowledge of SpaceX/Starlink.

4. Satellite Network Integrated with Internet

Since there is no complete satellite network established yet, all following analysis is based on the predictions from the traditional GEO communication. The analysis also learnt how other type of network has been used in Internet, such as Broadband access network, Mobile access network, Enterprise network and Service Provider network.

As a criteria to be part of Internet, any device connected to any satellite should be able to communicate with any public IP4 or IPv6 address in Internet. There could be three types of methods to deliver IP packet from source to destination by satellite:

1. **Data packet is relayed between ground station and satellite.** For this method, there is no inter-satellite communication and networking. Data packet is bounced once or couple times between ground stations and satellites until the packet arrives at the destination in Internet.

2. **Data packet is delivered by inter-satellite networking.** For this method, the data packet traverses with multiple satellites connected by ISL and inter-satellite networking is used to deliver the packet to the destination in Internet.

3. **Both satellite relay and inter-satellite networking are used.** For this method, the data packet is relayed in some segments and traverse with multiple satellites in other segments. It is a combination of the method 1 and method 2.

Using the above methods for IP packet delivery via satellite network, we will have two typical use cases for satellite network. One is for the general broadband access (see Section 4.1), another is for the integration with 3GPP wireless network including 4G and 5G (see Section 4.2 and Section 4.3).

4.1. Use Satellite Network for Broadband Access

For this use case, the end user terminal or local network is connected to a ground station, and another ground station is connected to Internet. Two ground stations will have IP connectivity via a satellite network. The satellite network could be by satellite relays or by inter-satellite network.

Follows are typical deployment scenarios that a Satellite network is used for broadband access of Internet.

1. **The end user terminal access Internet through satellite relay** (Figure 1 for one satellite relay, Figure 2 for multiple satellite relay).

networking

2. The end user terminal access Internet through inter-satellite-networking

(Figure 3).

3. The local network access Internet through satellite relay

(Figure 4 for one satellite relay, Figure 5 for multiple satellite relay).

4. The local network access Internet through inter-satellite-networking

(Figure 6).

```
          S1----\            /-----------\
         /       \          /             \
T---GW--GS1--S2--GS2-------PE   Internet   +
         \       /          \             /
          \---S3/            \-----------/
```

Figure 1: End user terminal access Internet through one satellite relay

```
          S1----\    S4----\       /-----------\
         /       \  /       \     /             \
T---GW--GS1--S2--GS2---S5--GS3---PE   Internet   +
         \       /  \       /     \             /
          \---S3/    \---S6/       \-----------/
```

Figure 2: End user terminal access Internet through multiple satellite relay

```
          S1-----S2-----S3--\            /----------\
         /                   \          /            \
T---GW--GS1--S4----S5---S6---GS2-------PE  Internet   +
         \                   /          \            /
          \---S7----S8----S9/            \----------/
```

Figure 3: End user terminal access Internet through inter-satellite-networking

```
  /-----------\           S1----\           /-------\
 /             \         /       \         /         \
+ Local network CE------GS1--S4--GS2-------PE Internet +
 \             /         \       /         \         /
  \-----------/           \---S7/           \-------/
```

Figure 4: Local network access Internet through one satellite relay

```
      /-----------\         S1----\   S4----\       /-------\
     /             \       /       \  /      \     /         \
    + Local network CE----GS1--S2--GS2--S5--GS3---PE Internet +
     \             /       \       / \       /     \         /
      \-----------/         \---S3/   \---S6/       \-------/
```

Figure 5: Local network access Internet through multiple satellite relay

```
  /-----------\          S1-----S2-----S3---\            /------\
 /             \        /                    \          /        \
+ Local network CE------GS1--S4----S5---S6---GS2-------PE Internet+
 \             /        \                    /          \        /
  \-----------/          \---S7----S8----S9/             \------/
```

Figure 6: Local network access Internet through inter-satellite-networking

In above Figure 1 to Figure 6, the meaning of symbols are as follows:

T The end user terminal

GW Gateway router

GS1, GS2, GS3 Ground station with L2/L3 routing/switch functionality.

S1 to S9 Satellites

PE Provider Edge Router

CE Customer Edge Router

4.2. Use Satellite Network with 3GPP Wireless Access Network

For this use case, the wireless access network (4G, 5G) defined in 3GPP is used with satellite network. By such integration, a user terminal or local network can access Internet via 3GPP wireless network and satellite network. The End user terminal or local network access Internet through satellite network and Mobile Access Network. There are two cases: 1) From mobile access network to satellite network or 2) From satellite network to mobile access network, Satellite network includes inter satellite network and relay network. See Figure 7 for mobile access network to satellite network, and Figure 8 for satellite network to mobile access network.

```
+--------------+    +-------------+    +---------+    +--------+
|    T or      |    |Mobile Access|    |Satellite|    |Internet|
| Local network+----+  Network    +----+ Network +----+        |
+--------------+    +-------------+    +---------+    +--------+
```

Figure 7: End user terminal or local network access Internet through Mobile Access Network and Satellite Network

```
+--------------+   +---------+   +-------------+   +--------+
|    T or      |   |Satellite|   |Mobile Access|   |Internet|
| Local network+---+ Network +---+  Network    +---+        |
+--------------+   +---------+   +-------------+   +--------+
```

Figure 8: End user terminal or local network access Internet through Satellite Network and Mobile Access Network

4.3. Recent Development and Study in 3GPP for Satellite Network

3GPP SA Working Groups (WG) feature a couple of satellite-related projects (or SIDs). The SA2 WG is currently studying the adoption of satellite communication to provide 5G backhaul service [TR-23.700-27].

One key aspect is to investigate the potential architecture requirements and enhancements to deploy UPFs on satellites (LEO/MEO/GEO) with gNBs on the ground. Specifically, it targets at enhancing the local-switching capability for UE-to-UE data communication when UEs are served by UPFs on-board satellite(s). Similarly, the SA1 WG proposed a new satellite-based SID in which the service end points (could also be called UEs in a broader sense) may continuously move in a fast way. The UEs can be ships, boats, and cars, etc., which are located in remote regions that need the connection to LEO's for achieving communication.

In all the SIDs, satellite based backhaul is important for mission critical scenarios in remote areas. Here, we want to clarify that while 3GPP documents TS 23.501 [TS-23.501] and 23.502 [TS-23.502] specify that a ground base station, i.e., gNB, may have multiple types of satellite backhauls (BH), e.g., GEO BH, LEO BH and LEO-BH with ISL, this use case focuses specifically on the LEO-BH with ISL. ISL stands for inter-satellite link.

Clearly, when a satellite backhaul involves multi-hop ISL path connected via different satellites, the capabilities provided by the satellite path would be changed and adjusted dynamically. For example, in the LEO case, the peering relationship between two neighboring satellites changes roughly every 5 minutes thanks to the orbital movement (see Table 2). This will definitely impair the networking performance and stability, and, in worst case, may cause the loss of connectivity. Even if some overlay tunneling mechanisms could be used to address the multi-hop ISL issue, the extra delay and potentially less bandwidth as introduced naturally by the ever-changing backhaul path would still impact the traffic engineering over the links.

The following diagram Figure 9 demonstrate the dynamic characteristics of satellite backhaul between two UEs. In the figure, UEs are connected, via gNBs, to UPFs on-board satellites. Both UPFs are connected via multi-hop ISLs to the 5G core (5GC) on the ground. There are two different multi-hop ISL paths: o A UE has to rely on a multi-hop ISL path to connect to 5GC on the ground. o When two UEs intend to communicate via the local data switching on satellite(s), some new ISL-based peering has to be established which would bring in the multi-hop ISL scenario. For example, the ISL between the Sat#1 and Sat#2 helps form a multi-hop path (marked N19 in the diagram) between the two UEs. Note that if the UPF-based local data switching involves only one UPF, then it is designated as intra-UPF local switching and relatively simpler. This is compared to the case of inter-UPF local switching as shown in the diagram.

```
    Sat#: Satellite                     GS:  Ground Station
    UPF:  User Plane Function (5G)      gNB: Next Generation NodeB

                     Sat#1
                +-----------+      +---------+
                |  UPF#1    | (ISL) | Sat#.. |
   UE#1--gNB#1--|(on-board)|- - - -|        |-----+
                +-----------+      +---------+     |
                     :                             |      --------
                     :(N19)                        v     /        \
                     :(ISL)                       GS ---+ 5G Core +
                     :                             ^     \        /
                +-----------+      +---------+     |      --------
                |  UPF#2    | (ISL) | Sat#.. |     |
   UE#2--gNB#2--|(on-board)|- - - -|        |-----+
                +-----------+      +---------+
                   Sat#2
```

Figure 9: Use Satellite network as back haul for 5G

In this diagram, both UEs are served by different satellite backhauls. If the local data switching via LEO UPFs on-board could be established (via the N19 ISL forwarding), then the system efficiency and QoE improvement would be achieved. Here, since UEs are served by different satellites, a multi-hop ISL scenario must be supported. But, this scenario posts challenges due to the dynamic satellite network topology and distinguished transmission capabilities from different satellites.

For example, if the UE-to-UE session has to maintain a service over longer time (> 5 minutes) such that the Sat#1 and Sat#2 move apart, then a new ISL path with potentially a new N19-ISL might be established. In worst case, if newly-involved satellites in the path happen to be polar-orbit ones and they do not support cross-seam ISLs, the communication latency may change dramatically when cross-seam transits or leaves. In another example, if both UEs belong to the same entity and need to form a 5G-VN group, then the 5G LAN-type service with PSA UPF-based local-switching must be applied among them.

Regardless, more efficient satellite communication mechanisms must be adopted, e.g., running efficient satellite-based routing protocols, establishing tunnels between LEO UPFs on-board, etc., for better local-data switching.

Further, 5GS may collaborate with satellite networks to improve QoS. One 5GC NF (i.e., SMF) can initiate UP path monitoring, and accordingly receive UP path monitoring results indicating observed delay. After that, the SMF takes corresponding actions like further verifying network statistics, updating sessions, etc. The coordination with the satellite networks would improve the process, which suggests satellites networks respond better to the (monitor-based) polling from 5GS.

One more thing we want to point out is that, while the propagation delay of satellite backhaul paths may change dramatically with the movement of satellite, this kind of change normally be periodic and can be well predicated based on the operation information of satellite constellation. Thus, making use of these information would also help for better services.

5. Problems and Requirements for Satellite Constellation for Internet

As described in Section 4, satellites in a satellite constellation can either relay internet traffic or multiple satellites can form a network to deliver internet traffic. More detailed analysis are in following sub sections. There might have multiple solutions for each method described in Section 4, following contexts only discuss the most plausible solution from networking perspectives.

Section 5.1 will list the common problems and requirements for both satellite relay and satellite networking.

Section 5.2 and Section 5.3 will describe key problems, requirement and potential solution from the networking perspective for these two cases respectively.

5.1. Common Problems and Requirements

For both satellite relay and satellite networking, satellite-ground-station communication must be used, so, the problems and requirements for the satellite-ground-station communication is common and will apply for both methods.

When one satellite is communicating with ground station, the satellite only needs to receive data from uplink of one ground station, process it and then send to the downlink of another ground station. Figure 1 illustrates this case. Normally microwave is used for both links.

Additionally, from the coverage analysis in Appendix A.2 and real deployment in Appendix A.3, we can see one ground station may communicate with multiple satellites. Similarly, one satellite may communicate with multiple ground stations. The characters for satellite-ground-station communication are:

1. **Satellite-ground-station communication is P2MP.**
   Since microwave physically is the carrier of broadcast communication, one satellite can send data while multiple ground stations can receive it. Similarly, one ground station can send data and multiple satellites can receive it.

2. **Satellite-ground-station communication is in open space and not secure.**
   Since electromagnetic fields for microwave physically are propagating in open space. The satellite-ground-station communication is also in open space. It is not secure naturally.

3. **Satellite-ground-station communication is not steady.**
   Since the satellite is moving with high speed, from Appendix B.1, the satellite-ground-station communication can only last a certain period of time. The communication peers will keep changing.

4. **Satellite-to-Satellite communication is not steady.**
   For some satellites, even they are in the same altitude and move in the same speed, but they move in the opposite direction, from Appendix B.2.2, the satellite-to-satellite communication can only last a certain period of time. The communication peers will keep changing.

5. **Satellite-to-Satellite distance is not steady.**
   For satellites with the same altitude and same moving direction, even their relative position is steady, but the distance between satellites are not steady. This will lead to the inter-satellite-communication's bandwidth and latency keep changing.

6. Satellite physical resource is limited.

Due to the weight, complexity and cost constraint, the physical resource on a satellite, such as power supply, memory, link speed, are limited. It cannot be compared with the similar device on ground. The design and technology used should consider these factors and take the appropriate approach if possible.

The requirements of satellite-ground-station communication are:

R1. The bi-directional communication capability

Both satellites and ground stations have the bi-directional communication capability

R2. The identifier for satellites and ground stations

Satellites and ground stations should have Ethernet and/or IP address configured for the device and each link. More detailed address configuration can be seen in each solution.

R3. The capability to decide where the IP packet is forwarded to.

In order to send Internet traffic or IP date to destination correctly, satellites and ground station must have Ethernet hub or switching or IP routing capability. More detailed capability can be seen in each solution.

R4. The protocol to establish the satellite-ground-station communication.

For security and management purpose, the satellite-ground-station communication is only allowed after both sides agree through a protocol. The protocol should be able to establish a secured channel for the communication when a new communication peer comes up. Each ground station should be able to establish multiple channels to communicate with multiple satellites. Similarly, each satellite should be able to establish multiple channels to communicate to multiple ground stations.

R5. The protocol to discover the state of communication peer.

The discover protocol is needed to detect the state of communication peer such as peer's identity, the state of the peer and other info of the peer. The protocol must be running securely without leaking the discovered info.

R6. The internet data packet is forwarded securely.

When satellite or ground station is sending the IP packet to its peer, the packet must be relayed securely without leaking the user data.

R7. The internet data packet is processed efficiently on satellite

Due to the resource constraint on a satellite, the packet may need more efficient mechanism to be processed on satellite. The process on satellite should be very minimal and offloaded to ground as much as possible.

5.2. Satellite Relay

One of the reasons to use satellite constellation for internet access is it can provide shorter latency than using the fiber underground. But using ISL for inter-satellite communication is the premise for such benefit in latency. Since the ISL is still not mature and adopted commercially, satellite relay is a only choice currently for satellite constellation used for internet access. In [UCL-Mark-Handley], detailed simulations have demonstrated better latency than fiber network by satellite relay even the ISL is not present.

5.2.1. One Satellite Relay

One satellite relay is the simplest method for satellite constellation to provide Internet service. By this method, IP traffic will be relayed by one satellite to reach the DGS and go to Internet.

The solution option and associated requirements are:

S1. The satellite only does L1 relay or the physical signal process.

For this solution, a satellite only receives physical signal, amplify it and broadcast to ground stations. It has no further process for packet, such as L2 packet compositing and processing, etc. All packet level work is done only at ground station. The requirements for the solution are:

R1-1. SGS and BGS are configured as IP routing node. Routing protocol is running in SGS and BGS

SGS and BGS is a IP peer for a routing protocol (IGP or BGP). SGS will send internet traffic to DGS as next hop through satellite uplink and downlink.

R1-2. DGS must be connected with Internet.

DGS can process received packet from satellite and forward the packet to the destination in Internet.

In addition to the above requirements, following problem should be solved:

P1-1. IP continuity between two ground stations

This problem is that two ground stations are connected by one satellite relay. Since the satellite is moving, the IP continuity between ground stations is interrupted by satellite changing periodically. Even though this is not killing problem from the view point that IP service traditionally is only a best effort service, it will benefit the service if the problem can be solved. Different approaches may exist, such as using hands off protocols, multipath solutions, etc.

S2. The satellite does the L2 relay or L2 packet process.

For this solution, IP packet is passing through individual satellite as an L2 capable device. Unlike in the solution S1, satellite knows which ground station it should send based on packet's destination MAC address after L2 processing. The advantage of this solution over S1 is it can use narrower beam to communicate with DGS and get higher bandwidth and better security. The requirements for the solution are:

R2-1. Satellite must have L2 bridge or switch capability

In order to forward packet to properly, satellite should run some L2 process such as MAC learning, MAC switching. The protocol running on satellite must consider the fast movement of satellite and its impact to protocol convergence, timer configuration, table refreshment, etc.

R2-2. same as R1-1 in S1

R2-3. same as R1-2 in S1

In addition to the above requirements, the problem P1-1 for S1 should also apply.

5.2.2. Multiple Satellite Relay

For this method, packet from SGS will be relayed through multiple intermediate satellites and ground station until reaching a DGS.

This is more complicated than one satellite relay described in Section 5.2.1.

One general solution is to configure both satellites and ground-stations as IP routing nodes, proper routing protocols are running in this network. The routing protocol will dynamically determine forwarding path. The obvious challenge for this solution is that all links between satellite and ground station are not static, according to the analysis in Appendix B.1, the lifetime of each link may last only couple of minutes. This will result in very quick and constant topology changes in both link state and IP adjacency, it will cause the distributed routing algorithms may never converge. So this solution is not feasible.

Another plausible solution is to specify path statically. The path is composed of a serials of intermediate ground stations plus SGS and DGS. This idea will make ground stations static and leave the satellites dynamic. It will reduce the fluctuation of network path, thus provide more steady service. One variant for the solution is whether the intermediate ground stations are connected to Internet. Separated discussion is as below:

S1. Manual configuring routing path and table

For this solution, the intermediate ground stations and DGS are specified and configured manually during the stage of network planning and provisioning. Following requirements apply:

R1-1. Specify a path from SGS to DGS via a list of intermediate ground stations.
The specified DGS must be connected with internet. Other specified intermediate ground stations does not have to

R1-2. All Ground stations are configured as IP routing node.
Static routing table on all ground stations must be pre-configured, the next hop of routes to Internet destination in any ground station is configured to going through uplink of satellite to the next ground station until reaching the DGS.

R1-3. All Satellites are configured as either L1 relay or L2 relay.
The Satellite can be configured as L1 relay or L2 relay described in S1 and S2 respectively in Section 5.2.1

In addition to the above requirements, the problem P1-1 in Section 5.2.1 should also apply.

S2. Automatic decision by routing protocol.

This solution is only feasible after the IP continuity problem (P1-1 in Section 5.2.1) is solved. Following requirements apply:

R2-1. All Ground stations are configured as IP routing node. Proper routing protocols are configured as well.
The satellite link cost is configured to be lower than the ground link. In such a way, the next hop of routes for the IP forwarding to Internet destination in any ground station will be always going through the uplink of satellite to the next ground station until reaching the DGS.

R2-2. All Satellites are configured as either L1 relay or L2 relay.
The Satellite can be configured as L1 relay or L2 relay described in S1 and S2 respectively in Section 5.2.1

In addition to the above requirements, the problem P1-1 in Section 5.2.1 should also apply.

5.3. Satellite Networking by ISL

In the draft, satellite Network is defined as a network that satellites are inter-connected by inter-satellite links (ISL). One of the major difference of satellite network with the other type of network on ground (telephone, fiber, etc.) is its topology and links are not stationary, some new issues have to be considered and solved. Follows are the factors that impact the satellite networking.

5.3.1. L2 or L3 network

The 1st question to answer is should the satellite network be configured as L2 or L3 network? As analyzed in Appendix A.2 and Appendix A.3, since there are couple of hundred or over ten thousand satellites in a network, L2 network is not a good choice, instead, L3 or IP network is more appropriate for such scale of network.

5.3.2. Inter-satellite-Link Lifetime

If we assume the orbit is circular and ignore other trivial factors, the satellite speed is approximately determined by the orbit altitude as described in the Appendix B.1. The satellite orbit can determine if the dynamic position of two satellites is within the range of the inter-satellite communication. That is 2000km for laser communication [Laser-communication-range] by Inter Satellite Laser Link (ISLL).

When two satellites' orbit planes belong to the same group, or two orbit planes share the same altitude and inclination, and when the satellites move in the same direction, the relative positions of two satellites are relatively stationary, and the inter-satellite communication is steady. But when the satellites move in the opposite direction, the relative positions of two satellites are not stationary, the communication lifetime is couple of minutes. The Appendix B.2.2 has analyzed the scenario.

When two satellites' orbit planes belong to the different group, or two orbit planes have different altitude, the relative position of two satellite are unstable, and the inter-satellite communication is not steady. As described in Appendix B.2, The life of communication for two satellites depends on the following parameters of two satellites:

1. The speed vectors.

2. The altitude difference

3. The intersection angle

From the examples shown in Table 4 to Table 7, we can see that the lifetime of inter-satellite communication for the different group of orbit planes are from couple of hundred seconds to about 18 hours. This fact will impact the routing technologies used for satellite network and will be discussed in Section 5.3.3.

5.3.3. Problems for Traditional Routing Technologies

When the satellite network is integrated with Internet by traditional routing technologies, following provisioning and configuration (see Figure 10) will apply:

1. The ground stations connected to local network and internet are treated as PE router for satellite network (called PE_GS1 and PE_GS2 in the following context), and all satellites are treated as P router.

2. All satellites in the network and ground stations are configured to run IGP.

3. The eBGP is configured between PE_GS and its peered network's PE or CE.

The work on PE_GS1 are:

* The local network routes are received at PE_GS1 from CE by eBGP. The routes are redistributed to IGP and then IGP flood them to all satellites. (Other more efficient methods, such as iBGP or BGP reflectors are hard to be used, since the satellite is moving and there is no easy way to configure a full meshed iBGP session for all satellites, or configure one satellite as BGP reflector in satellite network.)

* The internet routes are redistributed from IGP to eBGP running on PE_GS1, and eBGP will advertise them to CE.

The work on PE_GS2 are:

* The Internet routes are received at PE_GS2 from PE by eBGP. The routes are redistributed to IGP and then IGP flood them to all satellites. (Similar as in PE_GS1, Other more efficient methods, such as iBGP or BGP reflector cannot be used.)

* The local network routes are redistributed from IGP to eBGP running on PE_GS2, and eBGP will advertise them to Internet.

```
  /--------\             S1---S2----S3----\              /------\
 /          \           /    IGP domain   \            /        \
+ Local net CE--eBGP--PE_GS1---S4---S5---PE_GS2--eBGP--PE Internet +
 \          /           \                 /            \        /
  \--------/             \---S6---S7---S8/              \------/
```

Figure 10: Local access Internet through inter-satellite-networking

Local access Internet through inter-satellite-networking

On PE-GS1, due to the fact that IGP link between PE_GS1 and satellite is not steady; this will lead to following routing activity:

1. When one satellite is connecting with PE_GS1, the satellite and PE_GS1 form a IGP adjacency. IGP starts to exchange the link state update.

2. The local network routes received by eBGP in PE_GS1 from CE are redistributed to IGP, and IGP starts to flood link state update to all satellites.

3. Meanwhile, the Internet routes learnt from IGP in PE_GS1 will be redistributed to eBGP. eBGP starts to advertise to CE.

4. Every satellite will update its routing table (RIB) and forwarding table (FIB) after IGP finishes the SPF algorithm.

5. When the satellite is disconnecting with PE-GS1, the IGP adjacency between satellite and PE_GS1 is gone. IGP starts to exchange the link state update.

6. The routes of local network and satellite network that were redistributed to IGP in step 2 will be withdrawn, and IGP starts to flood link state update to all satellites.

7. Meanwhile, the Internet routes previously redistributed to eBGP in step 3 will also be withdrawn. eBGP starts to advertise route withdraw to CE.

8. Every satellite will update its routing table (RIB) and forwarding table (FIB) after the SPF algorithm.

Similarly on PE_GS2, due to the fact that IGP link between PE_GS2 and satellite is not steady; this will lead to following routing activity:

1. When one satellite is connecting with PE_GS2, the satellite and PE_GS2 form a IGP adjacency. IGP starts to exchange the link state update.

2. The Internet routes previously received by eBGP in PE_GS2 from PE are redistributed to IGP, IGP starts to flood the new link state update to all satellites.

3. Meanwhile, the routes of local network and satellite network learnt from IGP in PE_GS2 will be redistributed to eBGP. eBGP starts to advertise to Internet peer PE.

4. Every satellite will update its routing table (RIB) and forwarding table (FIB) after IGP finishes the SPF algorithm.

5. When the satellite is disconnecting with PE-GS2, the IGP adjacency between satellite and PE_GS2 is gone. IGP starts to exchange the link state update.

6. The internet routes previously redistributed to IGP in step 2 will be withdrawn, and IGP starts to flood link state update to all satellites

7. Meanwhile, the routes of local network and satellite network previously redistributed to eBGP in step 3 will also be withdrawn. eBGP starts to advertise route withdraw to PE.

8. Every satellite will update its routing table (RIB) and forwarding table (FIB) after the SPF algorithm.

For the analysis of detailed events above, the estimated time interval between event 1 and 5 for PE_GS1 and PE_GS2 can use the analysis in Appendix B.1. For example, it is about 398s for LEO and 103s for VLEO. Within this time interval, the satellite network including all satellites and two ground stations must finish the works from 1 to 4 for PE_GS1 and PE_GS2. The normal internet IPv6 and IPv4 BGP routes size are about 850k v4 routes + 100K v6 routes [BGP-Table-Size]. There are couple critical problems associated with the events:

P1. Frequent IGP update for its link cost

Even for satellites in different orbit with the steady relative positions, the distance between satellites is keep changing. If the distance is used as the link cost, it means the IGP has to update the link cost frequently. This will make IGP keep running and update its routing table.

P2. Frequent IGP flooding for the internet routes

Whenever the IGP adjacency changes (step 1 and 5 for PE_GS2), it will trigger the massive IGP flooding for the link state update for massive internet routes learnt from eBGP. This will result in the IGP re-convergency, RIB and FIP update.

P3. Frequent BGP advertisement for the internet routes

Whenever the IGP adjacency changes (step 3 and 7 for PE_GS1), it will trigger the massive BGP advertisement for the internet routes learnt from IGP. This will result in the BGP re-convergency, RIB and FIB update. BGP convergency time is longer than IGP. The document [BGP-Converge-Time1] has shown that the BGP convergence time varies from 50sec to couple of hundred seconds. The analysis [BGP-Converge-Time2] indicated that per entry update takes about 150us, and it takes o(75s) for 500k routes, or o(150s) for 1M routes.

P4. More frequent IGP flooding and BGP update in whole satellite network

To provide the global coverage, a satellite constellation will have many ground stations deployed. For example, StarLink has applied for the license for up to one million ground stations [StarLink-Ground-Station-Fcc], in which, more than 50 gateway ground stations (equivalent to the PE_GS2) have been registered [SpaceX-Ground-Station-Fcc] and deployed in U.S. [StarLink-GW-GS-map]. It is expected that the gateway ground station will grow quickly to couple of thousands [Tech-Comparison-LEOs]. This means almost each satellite in the satellite network would have a ground station connected. , Due to the fact that all satellites are moving, many IGP adjacency changes may occur in a shorter period of time described in Appendix B.1 and result in the problem P1 and P2 constantly occur.

P5. Service is not steady

Due to the problems P1 to P3, the service provider of satellite constellation is hard to provide a steady service for broadband service by using inter-satellite network and traditional routing technologies.

As a summary, the traditional routing technology is problematic for large scale inter-satellite networking for Internet. Enhancements on traditional technologies, or new technologies are expected to solve the specific issues associated with satellite networking.

6. IANA Considerations

This memo includes no request to IANA.

7. Security Considerations

Security considerations for communication between satellite and ground station, or between satellites are described in corresponding sections. There is no extra security issue introduced by this memo.

8. Contributors

9. Acknowledgements

10. References

10.1. Normative References

[RFC4271] Rekhter, Y., Ed., Li, T., Ed., Hares, S., Ed., and RFC Publisher, "A Border Gateway Protocol 4 (BGP-4)", RFC 4271, DOI 10.17487/RFC4271, January 2006, <https://www.rfc-editor.org/info/rfc4271>.

[RFC2328] Moy, J. and RFC Publisher, "OSPF Version 2", STD 54, RFC 2328, DOI 10.17487/RFC2328, April 1998, <https://www.rfc-editor.org/info/rfc2328>.

[RFC7142] Shand, M., Ginsberg, L., and RFC Publisher, "Reclassification of RFC 1142 to Historic", RFC 7142, DOI 10.17487/RFC7142, February 2014, <https://www.rfc-editor.org/info/rfc7142>.

[RFC2453] Malkin, G. and RFC Publisher, "RIP Version 2", STD 56, RFC 2453, DOI 10.17487/RFC2453, November 1998, <https://www.rfc-editor.org/info/rfc2453>.

[RFC7868] Savage, D., Ng, J., Moore, S., Slice, D., Paluch, P., White, R., and RFC Publisher, "Cisco's Enhanced Interior Gateway Routing Protocol (EIGRP)", RFC 7868, DOI 10.17487/RFC7868, May 2016, <https://www.rfc-editor.org/info/rfc7868>.

10.2. Informative References

[KeplerianElement] "Keplerian elements", <https://en.wikipedia.org/wiki/Orbital_elements>.

[GEO-Coverage] "Coverage of a geostationary satellite at Earth", <https://www.planetary.org/space-images/coverage-of-a-geostationary>.

[Nttdocomo-6G] "NTTDPCOM 6G White Paper", <https://www.nttdocomo.co.jp/english/binary/pdf/corporate/

technology/whitepaper_6g/DOCOMO_6G_White_PaperEN_20200124.pdf>.

[ITU-6G] "ITU 6G vision", <https://www.itu.int/dms_pub/itu-s/opb/itujnl/S-ITUJNL-JFETF.V1I1-2020-P09-PDF-E.pdf>.

[Surrey-6G] "Surrey 6G vision", <https://www.surrey.ac.uk/sites/default/files/2020-11/6g-wireless-a-new-strategic-vision-paper.pdf>.

[OSI-Model] "OSI Model", <https://en.wikipedia.org/wiki/OSI_model>.

[StarLink] "Star Link", <https://en.wikipedia.org/wiki/Starlink>.

[China-constellation] "China Constellation", <https://www.itu.int/ITU-R/space/asreceived/Publication/DisplayPublication/23706>.

[ESA-HydRON] "HydRON: Fiber in the sky", <https://www.esa.int/ESA_Multimedia/Videos/2021/04/HydRON_Fibre_in_the_sky>.

[SpaceX-Non-GEO] "FCC report: SPACEX V-BAND NON-GEOSTATIONARY SATELLITE SYSTEM", <https://fcc.report/IBFS/SAT-LOA-20170301-00027/1190019.pdf>.

[Satellite-coverage] Alan R.Washburn, Department of Operations Research, Naval Postgraduate School, "Earth Coverage by Satellites in Circular Orbit", <https://faculty.nps.edu/awashburn/Files/Notes/EARTHCOV.pdf>.

[Microwave-vs-Laser-communication]
International Journal for Research in Applied Science and Engineering Technology (IJRASET), "Comparison of Microwave and Optical Wireless Inter-Satellite Links", <https://www.ijraset.com/fileserve.php?FID=7815>.

[Laser-communication-range] "Interferometric optical communications can potentially lead to robust, secure, and naturally encrypted long-distance laser communications in space by taking advantage of the underlying physics of quantum entanglement.", <https://www.laserfocusworld.com/optics/article/16551652/interferometry-quantum-entanglement-physics-secures-spacetospace-interferometric-communications>.

[BGP-Table-Size] "BGP in 2020 - BGP table", <https://blog.apnic.net/2021/01/05/bgp-in-2020-the-bgp-table/>.

[BGP-Converge-Time1] "BGP in 2020 - BGP Update Churn", <https://labs.apnic.net/?p=1397>.

[BGP-Converge-Time2] "Bringing SDN to the Internet, one exchange point at the time", <https://www.cs.princeton.edu/courses/archive/fall14/cos561/docs/SDX.pdf>.

[StarLink-Ground-Station-Fcc] "APPLICATION FOR BLANKET LICENSED EARTH STATIONS", <https://fcc.report/IBFS/SES-LIC-INTR2019-00217/1616678>.

[SpaceX-Ground-Station-Fcc] "List of SpaceX applications for ground stations", <https://fcc.report/IBFS/Company/Space-Exploration-Technologies-Corp-SpaceX>.

[Tech-Comparison-LEOs] "A Technical Comparison of Three Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband", <http://www.mit.edu/~portillo/files/Comparison-LEO-IAC-2018-slides.pdf>.

[StarLink-GW-GS-map] "StarLink gateway ground station map", <https://www.google.com/maps/d/u/0/viewer?mid=1H1x8jZs8vfjy60TvKgpbYs_grargieVw>.

[UCL-Mark-Handley] "Using ground relays for low-latency wide-area routing in megaconstellations", <https://discovery.ucl.ac.uk/id/eprint/10090242/1/hotnets-ucl.pdf>.

[TR-23.700-27] 3GPP, "Study on support of satellite backhauling in 5GS", May 2022.

[TS-23.501] 3GPP, "System architecture for the 5G System (5GS)", December 2021.

[TS-23.502] 3GPP, "Procedures for the 5G System (5GS)", December 2021.

Appendix A. Basics of Satellite Constellation

This section will introduce some basics for satellite such as orbit parameters, coverage estimation, minimum number of satellite and orbit plane required, real deployments.

A.1. Satellite Orbit

The orbit of a satellite can be either circular or ecliptic, it can be described by following Keplerian elements [KeplerianElement]:

1. Inclination (i)

2. Longitude of the ascending node (Omega)

3. Eccentricity (e)

4. Semimajor axis (a)

5. Argument of periapsis (omega)

6. True anomaly (nu)

For a circular orbit, two parameters, Inclination and Longitude of the ascending node, will be enough to describe the orbit.

A.2. Coverage of LEO and VLEO Satellites and Minimum Number Required

The coverage of a satellite is determined by many physical factors, such as spectrum, transmitter power, the antenna size, the altitude of satellite, the air condition, the sensitivity of receiver, etc. EIRP could be used to measure the real power distribution for coverage. It is not deterministic due to too many variants in a real environment. The alternative method is to use the minimum elevation angle from user terminals or gateways to a satellite. This is easier and more deterministic. [SpaceX-Non-GEO] has suggested originally the minimum elevation angle of 35 degrees and deduced the radius of the coverage area is about 435km and 1230km for VLEO (altitude 335.9km) and LEO (altitude 1150km) respectively. The details about how the coverage is calculated from the satellite elevation angle can be found in [Satellite-coverage].

Using this method to estimate the coverage, we can also estimate the minimum number of satellites required to cover the earth surface.

It must be noted, SpaceX has recently reduced the required minimum elevation angle from 35 degrees to 25 degrees. The following analysis still use 35 degrees.

Assume there is multiple orbit planes with the equal angular interval across the earth surface (The Longitude of the ascending node for sequential orbit plane is increasing with a same angular interval). Each orbit plane will have:

1. The same altitude.

2. The same inclination of 90 degree.

3. The same number of satellites.

With such deployment, all orbit planes will meet at north and south pole. The density of satellite is not equal. Satellite is more dense in the space above the polar area than in the space above the equator area. Below estimations are made in the worst covered area, or the area of equator where the satellite density is the minimum.

Figure 11 illustrates the coverage area on equator area, and each satellite will cover one hexagon area. The figure is based on plane geometry instead of spherical geometry for simplification, so, the orbit is parallel approximately.

Figure 12 shows how to calculate the radius (Rc) of coverage area from the satellite altitude (As) and the elevation angle (b).

```
                              x
                   |          |
                   |          |
                   x      *********
                   |     *    |    *
                   |    *     |     *
               *********      x      *
              *    |    *     |     *
             *     |     *    |    *
            *      x      *********
             *     |     *    |
              *    |    *     |
               *********      x
                   |          |
                   |       orbit 2          ^ north
                   x                        |
                   |                        |
                   |                        |
                 orbit 1                    +-------> east
```

Figure 11: Satellite coverage on ground

```
                       |<---  2*Rc --->|

                               + Satellite
                              /|
                             / |
                            /  |
                           / b |
                          /-\  +
                         /   * |     __Earth surface
                        /  *   |    /
                       / *_----+----__
                       +               +
                        *             *
                         *           *
                          *   2*a   *
                           *  ___  *
                            *-   -*
                             *   *
                              * *
                               * Earth center
```

Figure 12: Satellite coverage estimation

x The vertical projection of satellite to Earth

Re The radius of the Earth, Re=6378(km)

As The altitude of a satellite

Rc The radius (arc length) of the coverage, or, the arc length of hexagon center to its 6 vertices. Rc=Re*(a*pi)/180

a The cap angle for the coverage area (the RC arc). a = arccos((Re/(Re+As))*cos(b))-b.

b The least elevation angle that a ground station or a terminal can communicate with a satellite, b = 35 degree.

Ns The minimum number of satellites on one orbit plane, it is equal to the number of the satellite's vertical projection on Earth, so, Ns = 180/(a*cos(30))

No The minimum number of orbit (with same inclination), it is equal to the number of the satellite orbit's vertical projection, so, No = 360/(a*(1+sin(30)))

For a example of two type of satellite LEO and VEO, the coverages are calculated as in Table 1:

Parameters	VLEO1	VLEO2	LEO1	LEO2
As(km)	335.9	450	1100	1150
a(degree)	3.907	5.078	10.681	11.051
Rc(km)	435	565	1189	1230
Ns	54	41	20	19
No	62	48	23	22

Table 1: Satellite coverage estimation for LEO and VLEO examples

A.3. Real Deployment of LEO and VLEO for Satellite Network

Obviously, the above orbit parameter setup is not optimal since the sky in the polar areas will have the highest density of satellite.

In the real deployment, to provide better coverage for the areas with denser population, to get redundance and better signal quality, and to make the satellite distance within the range of inter-satellite communication (2000km [Laser-communication-range]), more than the minimum number of satellites are launched. For example, different orbit planes with different inclination/altitude are used.

Normally, all satellites are grouped by orbit planes, each group has a number of orbit planes and each orbit plane has the same orbit parameters, so, each orbit in the same group will have:

1. The same altitude

2. The same inclination, but the inclination is less than 90 degrees. This will result in the empty coverage for polar areas and better coverage in other areas. See the orbit picture for phrase 1 for [StarLink].

3. The same number of satellites

4. The same moving direction for all satellites

The proposed deployment of SpaceX can be seen in [SpaceX-Non-GEO] for StarLink.

The China constellation deployment and orbit parameters can be seen in [China-constellation].

Appendix B. Communications for Satellite Constellation

Unlike the communication on ground, the communication for satellite constellation is much more complicated. There are two mobility aspects, one is between ground-station and satellite, another is between satellites.

In the traditional mobility communication system, only terminal is moving, the mobile core network including base station, front haul and back haul are static, thus an anchor point, i.e., PGW in 4G or UPF in 5G, can be selected for the control of mobility session. Unfortunately, when satellite constellation joins the static network system of Internet on ground, there is no such anchor point can be selected since the whole satellite constellation network is moving.

Another special aspect that can impact the communication is that the fast moving speed of satellite will cause frequent changes of communication peers and link states, this will make big challenges to the network side for the packet routing and delivery, session control and management, etc.

B.1. Dynamic Ground-station-Satellite Communication

All satellites are moving and will lead to the communication between ground station and satellite can only last a certain period of time. This will greatly impact the technologies for the satellite networking. Below illustrates the approximate speed and the time for a satellite to pass through its covered area.

In Table 2, VLEO1 and LEO3 have the lowest and highest altitude respectively, VLEO2 is for the highest altitude for VLEO. We can see that longest communication time of ground-station-satellite is less than 400 seconds, the longest communication time for VLEO ground-station-satellite is less than 140 seconds.

The "longest communication time" is for the scenario that the satellite will fly over the receiver ground station exactly above the head, or the ground station will be on the diameter line of satellite coverage circular area, see Figure 11.

Re
The radius of the Earth, Re=6378(km)

As The altitude of a satellite

AL The arc length(in km) of two neighbor satellite on the same orbit plane, AL=2*cos(30)*(Re+As)*(a*pi)/180

SD The space distance(in km) of two neighbor satellite on the same orbir plane, SD=2*(Re+As)*sin(AL/(2*(Re+As))).

V the velocity (in m/s) of satellite, V=sqrt(G*M/(Re+As))

G Gravitational constant, G=6.674*10^(-11)(m^3/(kg*s^2))

M Mass of Earth, M=5.965*10^24 (kg)

T The time (in second) for a satellite to pass through its cover area, or, the time for the station-satellite communication. T= ALs/V

Parameters	VLEO1	VLEO2	LEO1	LEO2	LEO3
As(km)	335.9	450	1100	1150	1325
a(degree)	3.907	5.078	10.681	11.051	12.293
AL(km)	793	1048	2415	2515	2863
SD(km)	792.5	1047.2	2404	2503.2	2846.1
V(km/s)	7.7	7.636	7.296	7.272	7.189
T(s)	103	137	331	346	398

Table 2: The time for the ground-station-satellite communication

B.2. Dynamic Inter-satellite Communication

B.2.1. Inter-satellite Communication Overview

In order to form a network by satellites, there must be an inter-satellite communication. Traditionally, inter-satellite communication uses the microwave technology, but it has following disadvantages:

1. Bandwidth is limited and only up to 600M bps [Microwave-vs-Laser-communication].

2. Security is a concern since the microwave beam is relatively wide and it is easy for 3rd party to sniff or attack.

3. Big antenna size.

4. Power consumption is high.

5. High cost per bps.

Recently, laser is used for the inter-satellite communication, it has following advantages, and will be the future for inter-satellite communication.

1. Higher bandwidth and can be up to 10G bps [Microwave-vs-Laser-communication].

2. Better security since the laser beam size is much narrower than microwave, it is harder for sniffing.

3. The size of optical lens for laser is much smaller than microwave's antenna size.

4. Power saving compared with microwave.

5. Lower cost per bps.

The range for satellite-to-satellite communications has been estimated to be approximately 2,000 km currently [Laser-communication-range].

From Table 2, we can see the Space Distance (SD) for some LEO (altitude over 1100km) are exceeding the celling of the range of laser communication, so, the satellite and orbit density for LEO need to be higher than the estimation values in the Table 1.

Assume the laser communication is used for inter-satellite communication, then we can analyze the lifetime of inter-satellite communication when satellites are moving. The Figure 13 illustrates the movement and relative position of satellites on three orbits. The inclination of orbit planes is 90 degrees.

```
    + North pole
   /|\
  | s |
 s  |  s
/   s   \
s   |   s
|   s1  |
s4  |   s6
|   s2  |   -------- Equator
s5  |   s7
|   s3  |
s   |   s
\   s   /
 s  |  s
  | s |
   \|/
    +  South pole
```

Figure 13: Satellite movement

There are four scenarios:

1. **For satellites within the same orbit**
   The satellites in the same orbit will move to the same direction with the same speed, thus the interval between satellites is relatively steady. Each satellite can communicate with its front and back neighbor satellite as long as satellite's orbit is maintained in its life cycle. For example, in Figure 13, s2 can communication with s1 and s3.

2. **For satellites between neighbor orbits in the same group at non-polar areas**
   The orbits for the same group will share the same orbit altitude and inclination. So, the satellite speed in different orbit are also same, but the moving direction may be same or different. Figure 14 illustrates this scenario. When the moving direction is the same, it is similar to the scenario 1, the relative position of satellites in different orbit are relatively steady as long as satellite's orbit is maintained in its life cycle. When the moving direction is different, the relative position of satellites in different orbit are un-steady, this scenario will be analyzed in more details in Appendix B.2.2.

3. **For satellites between neighbor orbits in the same group at polar areas**
   For satellites between neighbor orbits with the same speed and moving direction, the relative position is steady as described in #2 above, but the steady position is only valid at areas other than polar area. When satellites meet in the polar area, the

relative position will change dramatically. Figure 15 shows two satellites meet in polar area and their ISL facing will be swapped. So, if the range of laser pointing angle is 360 degrees and tracking technology supports, the ISL will not be flipping after passing polar area; Otherwise, the link will be flipping and inter-satellite communication will be interrupted.

4. **For satellites between different orbits in the different group**
   The orbits for the different group will have different orbit altitude, inclination and speed. So, the relative position of satellite is not static. The inter-satellite communication can only last for a while when the distance between two satellite is within the limit of inter-satellite communication, that is 2000km for laser [Laser-communication-range], this scenario will be analyzed in more details in Appendix B.2.3

```
            i+N/2         i+1+N/2       i+2+N/2
          / \           / \           / \
         /   \         /   \         /   \
        S1    \       S2    \       S3    \
       /       S4    /      S5     /      S6
      /         \   /         \   /         \
     /           \ /           \ /           \
     i-1           i             i+1
```

* The total number of orbit planes are N
* The number (i-1, i, i+1,...) represents the Orbit index
* The bottom numbers (i-1, i, i+1) are for orbit planes on which satellites (S1, S2, S3) are moving from bottom to up.
* The top numbers (i+N/2, i+1+N/2, i+2+N/2) are for orbit planes on which satellites (S4, S5, S6) are moving from up to bottom.

Figure 14: Two satellites with same altitude and inclination (i) move in the same or opposite direction

```
\      /
 P3   P4
  \  /
   \/
   /\
  /  \
 P1   P2
/      \
```

* Two satellites S1 and S2 are at position P1 and P2 at time T1
* S1's right facing ISL connected to S2's left facing ISL
* S1 and S2 move to the position P4 and P3 at time T2
* S1's left facing ISL connected to S2's right facing ISL

Figure 15: Two satellites meeting in the polar area will change its facing of ISL

B.2.2. Satellites on Adjacent Orbit Planes with Same Altitude

For satellites on different orbit planes with same altitude, the estimation of the lifetime when two satellite can communicate are as follows.

Figure 16 illustrates a general case that two satellites move and intersect with an angle A.

```
                  ^ V2
                 /
                /
               +-
              /  \ A
-------------+----+----> V1
            /
           /
```

Figure 16: Two satellites (speed vector V1 and V2) intersect with angle A

More specifically, for orbit planes with the inclination angle i, Figure 17 illustrates two satellites move in the opposite direction and intersect with an angle 2*i.

```
               ^ move from south to north
       \      /
        \    /
         \  /\
          \/  | A = 2*i
          /\  |
         /  \/
        /    \
       /      V move from north to south
```

Figure 17: Two satellites with same altitude and inclination (i) intersect with angle A=2*i

Follows are the math to calculate the lifetime of communication. Table 3 are the results using the math for two satellites with different altitudes and different inclination angles.

Dl The laser communication limit, Dl=2000km [Laser-communication-range]

A The angle between two orbit's vertical projection on Earth. A=2*i

V1 The speed vector of satellite on orbit1

V2 The speed vector of satellite on orbit2

|V| the magnitude of the difference of two speed vector V1 and V2, |V|=|V1-V2|=sqrt((V1-V2*cos(A))^2+(V2*sin(A))^2). For satellites with the same altitude and inclination angle i, V1=V2, so, |V| =V1*sqrt(2-2*cos(2*i))=2V1*sin(i)

T The lifetime two satellites can communicate, or the time of two satellites' distance is within the range of communication, T = 2*Dl/|V|.

i (degree)	80	80	65	65	50	50
Alt (km)	**500**	**800**	**500**	**800**	**500**	**800**
|V| (km/s)	14.98	14.67	13.79	13.5	11.66	11.41
T(s)	267	273	290	296	343	350

Table 3: The lifetime of communication for two LEOs (with two altitudes and three inclination angles)

B.2.3. Satellites on Adjacent Orbit Planes with Different Altitude

For satellites on different orbit planes with different altitude, the estimation of the lifetime when two satellite can communicate are as follows.

Figure 18 illustrates two satellites (with the altitude difference Da) move and intersect with an angle A.

```
                ^ V2
               /
              /
      -------+  /
      Da    /| +-
           / |/  \ A
----------/--+----+----> V1
         /  /
           /
          /
         /
```

Figure 18: Satellite (speed vector V1 and V2, Altitude difference Da) intersects with Angle A

Follows are the math to calculate the lifetime of communication

Dl The laser communication limit, Dl=2000km [Laser-communication-range]

Da Altitude difference (in km) for two orbit planes

A The angle between two orbit's vertical projection on Earth

V1 The speed vector of satellite on orbit 1

V2 The speed vector of satellite on orbit 2

|V| the magnitude of the difference of two speed vector V1 and V2, |v|=|V1-V2|=sqrt((V1-V2*cos(A))^2+(V2*sin(A))^2)

T The lifetime two satellites can communicate, or the time of two satellites' distance is within the range of communication, T = 2*sqrt(Dl^2-Da^2)/|V|

Using formulas above, below is the estimation for the life of communication of two satellites when they intersect. Table 4 and Table 5 are for two VLEOs with the difference of 114.1km for altitude. (VLEO1 and VLEO2 on Table 2). Table 6 and Table 7 are for two LEOs with the difference of 175km for altitude (LEO2 and LEO3 on Table 2).

Parameters	VLEO1	VLEO2
As(km)	335.9	450
V (km/s)	7.7	7.636

Table 4: Two VLEO with different altitude and speed

A (degree)	0	10	45	90	135	180
|V| (km/s)	0.065	1.338	5.869	10.844	14.169	15.336
T(s)	61810	2984	680	368	282	260

Table 5: Two VLEO intersects with different angle and the life of communication

Parameters	LEO1	LEO2
As(km)	1150	1325
V (km/s)	7.272	7.189

Table 6: Two LEO with different altitude and speed

A (degree)	0	10	45	90	135	180
|V| (km/s)	0.083	1.263	5.535	10.226	13.360	14.461
T(s)	47961	3155	720	390	298	276

Table 7: Two LEO intersects with different angle and the life of communication

Appendix C. Change Log

*Initial version, 07/03/2021

*01 version, 10/20/2021

*02 version, 2/13/2022

*03 version, 7/5/2022

*04 version, 1/4/2023

Authors' Addresses

Lin Han (editor)
Futurewei Technologies, Inc.
2330 Central Expy
Santa Clara, CA 95050,
United States of America

Email: lhan@futurewei.com

Richard Li
Futurewei Technologies, Inc.
2330 Central Expy
Santa Clara, CA 95050,

United States of America

Email: rli@futurewei.com

Alvaro Retana
Futurewei Technologies, Inc.
2330 Central Expy
Santa Clara, CA 95050,
United States of America

Email: alvaro.retana@futurewei.com

Meiling Chen
China Mobile
32, Xuanwumen West
BeiJing 100053
China

Email: chenmeiling@chinamobile.com

Li Su
China Mobile
32, Xuanwumen West
BeiJing 100053
China

Email: suli@chinamobile.com

Tianji Jiang
China Mobile
1525 McCathy Blvd.
Milpitas, CA 95035,
United States of America

Email: tianjijiang@chinamobile.com

Ning Wang
University of Surrey
Guildford
Surrey, GU2 7XH
United Kingdom

Email: n.wang@surrey.ac.uk