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Satellite Network Routing Use Cases

Abstract

Time-Variant Routing (TVR) is chartered and proposed to solve the problem of time-based, scheduled changes, including the variations of links, adjacencies, cost, and traffic volumes in some cases. In a satellite network, the network is in continual motion which will cause detrimental consequences on the routing issue. However, each network node in a satellite network follows a predefined orbit around the Earth and represents an appropriate example of time-based scheduled mobility. Therefore, TVR can be implemented to improve the routing and forwarding process in satellite networks. This document mainly focuses on the use cases in this scenario.

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1. Introduction

Since the beginning of the 21st century, the satellite network has become a significant part of information and communication infrastructure. The large-scale sallite network composed of thousands or even tens of thousands of LEO satellites, MEO satellites and GEO satellites can overcome the limitations of the conventional terrestrial network, achieving global signal coverage, and providing large broadband as well as low-latency network services for global users. The global communications ecosystem believes that satellite-based communication will become an important part of 5G-advanced and 6G.

In a satellite network, satellites move along the orbit, which can be divided into circular orbit satellites and elliptical orbit satellites. Different orbits can be described by Keplerian parameters, including inclination, longitude of the ascending node, eccentricity, semimajor axis, argument of periapsis, true anomaly. At present, the mainstream of satellite networks basically adopt circular orbit.

When links between satellites are established for end-to-end communication, each satellite usually has a fixed number of links which communicate with neighboring nodes, and considering the cost of satellite links and power restrictions of satellites, satellite links are generally limited to direct connections between adjacent nodes. In a single-layer satellite constellation, each satellite may have four types of contiguous neighbour satellites and each type refers to a direction. The number of neighbor satellites distributed in one direction is determined by the number of antennas deployed on the satellite for communication. If the satellite contains a single antenna in each direction, the connection relationship between the satellite N5 and its two satellites in the same orbit and two satellites in different adjacent orbits is shown in Figure 1. N2 and N8 are front and rear adjacent satellites in the same orbit plane which includes N5. N4 and N6 are left and right adjacent satellites which are adjacent to N5 locate in different orbit planes. In a multi-tier satellite constellation, each satellite may have two additional types of adjacent satellites, upper level satellites and lower level satellites in different tiers.

```
                 ^                      ^                      ^
                 |                      |                      |
                 |                      |                      |
                 v                      v                      v
                .--.                   .--.                   .--.
    <---> ####-| N1 |-#### <---> ####-| N2 |-#### <---> ####-| N3 |-#### <--->
                \__/                   \__/                   \__/
                 ^                      ^                      ^
                 |                      |                      |
                 |                      |                      |
                 v                      v                      v
                .--.                   .--.                   .--.
    <---> ####-| N4 |-#### <---> ####-| N5 |-#### <---> ####-| N6 |-#### <--->
                \__/                   \__/                   \__/
                 ^                      ^                      ^
                 |                      |                      |
                 |                      |                      |
                 v                      v                      v
                .--.                   .--.                   .--.
    <---> ####-| N7 |-#### <---> ####-| N8 |-#### <---> ####-| N9 |-#### <--->
                \__/                   \__/                   \__/
                 ^                      ^                      ^
                 |                      |                      |             N
                 |                      |                      |             ^
                 v                      v                      v             |
            Orbit plane 1          Orbit plane 2          Orbit plane 3      |
                                                                             S

                                                                        Moving
                                                                     Direction
```

Figure 1: N5 and its adjacent satellites

The satellite orbit velocity is related to the satellite orbit altitude (in a circular orbit), and satellites at the same altitude move at the same speed. Therefore, the relative position between satellites in the same orbit plane is stable and the intra-satellite links can always be connected, and the link distance is basically unchanged, such as N2 and N5. The relative position between satellites in different orbit planes changes dynamically, inter-satellite links may be interrrupted due to antenna tracking difficulties or limited communication range, and the physical distance of the link is constantly altering, such as N4 and N5.

As one of the indispensable issues for communication, routing strategies directly affects the transmission efficiency and the quality of network services. However, due to the particularity of the satellite network, such as the high frequency and intensity changes in network topology, the relatively mature terrestrial network routing technologies can not be directly applied to the satellite network. In view of the mentioned characteristics, and considering the combination of satellite networks and TVR, this document includes the following information:

1. The core problems of routing issues in satellite networks are stated and analyzed.
2. This paper discusses the unique time-based predictable network information in satellite networks, and proposes a routing optimization method based on this information.
3. The relevant application scenarios are given and illustrated.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Terminology

- LEO: Low Earth Orbit.
- MEO: Middle Earth Orbit.
- GEO: GEostationary Orbit.
- Intra-satellite links: Links between adjacent satellites in the same orbit.
- Intra-satellite links: Links between adjacent satellites in the different orbits.
- SGP4: Simplified Perturbations Models

4. Problem Analysis

The dynamic nature of nodes is the most significant feature of satellite networks compared to conventional terrestrial networks. In LEO mega-constellations, this feature becomes more obvious and prominent. Typical phenomena in satellite networks are listed here:

1. LEOs move at a relatively high speed for over 7km/s.
2. Half of LEOs in the network move in the same direction which is the opposite to the other half.
3. A great number of links between satellites or between satellites and ground-stations.
4. A large part of above links may be interrupted at specific areas.
5. All metrics of inter-satellite links are constantly changing.

6. All metrics of links between satellites and ground-stations are constantly changing.

Existing routing protocols are designated to maintain contemporaneous end-to-end connections across a network. Once the network topology or connection of links changes, corresponding operations and procedures are adopted to recover and maintain the reachability between various pairs. Representative procedures in traditional protocols may consist of attempting to re-establish lost adjacencies ,recalculating or rediscovering a valid path. The dynamic changes of network topologies and links in satellite networks will constantly trigger the process of routing re-convergence process with existing routing protocols, resulting in routing shocks, which makes it inappropriate for existing routing protocols to be directly applied in satellite networks.

5. Solution

The process of satellite motion along the orbit is periodic and predictable. Predictable information in a satellite network includes satellite real-time positions in the space, satellite link connectivity, and satellite link real-time metrics. The satellite-ground link also has similar characteristics, which have been described in [I-D.birrane-tvr-use-cases] and will not be repeated here.

(1) The real-time position of a satellite is predictable.

Satellites move around the earth in a predetermined orbit and are endowed with a unified and accurate count of time by a ground network control center or some specific designated nodes. Thus, the real-time position in the space of a satellite can be predicted in advance according to the satellite orbit parameters, the orbit injection moment and the satellite operation time.

(2) The connectivity of satellite links are predictable.

Due to the influence of the relative position changes between adjacent satellites in different orbits and the restrictions of current communication technologies, the inter-satellite link will be interrupted when entering a specific area and restored after leaving this regions. According to the satellite orbit parameters, satellite operation time, satellite attitude, and the communication range of the satellite antenna, combined with some specific algorithms, SGP4 (Simplified Perturbations Models) for instance, the connectivity of satellite links can be predicted in advance.

(3) The characteristics of satellite links are predictable.

Affected by the change of relative position between adjacent satellites in different orbits, the communication distance between satellites is constantly changing. This distance reaches the largest near the equator and declines to the smallest while moving to the pole. The changes in inter-satellite communication distance will further lead to the time-varying characteristic of inter-satellite links, such as propagation delay and bit error rate. According to satellite orbit parameters, satellite operation time, antenna transmission power, space propagation loss and so on, combined with proper algorithms, the characteristics of inter-satellite links can be predicted in advance.

As analyzed aboved, the management plane, the control plane and the forwarding plane of the network can be adaptively improved by utilizing time-based predictable information and combining the characteristics of inter satellite and satellite to ground transmission conditions, so as to ensure a stable and optimal end-to-end reachable path between a pair of satellites, such as:

(1) By improving the control plane protocol based on the predictability of the interruption/recovery of the satellite links, on one hand, the flooding of routing convergence information caused by network topology changes can be avoided, and on the other hand, the routing re-calculation is able to be fulfilled in advance before the satellite network topology changes, and thus the calculated results can be updated immediately and timely.The same methods can also apply to predictable changes in the characteristics of satellite links.

(2) By using the predictability of satellite spatial location, the routing algorithm can be improved, such as Dijkstra algorithm, which could screen relay nodes in the path without traversing all possible choices, and further reduce the complexity of the routing algorithm.

6. Use Cases

6.1. Scenario 1: Predictable changes in connectivities between satellites

As shown in Figure 2, N1, N2 and N3 are adjacent satellites in different orbit planes at the same altitude, moving from south to north. At T2 and T3, N3 and N2 enter a specific area (such as the polar region) in turn, and inter-satellite links are interrupted due to the difficulty in alignment of the on-board antenna. When the node leaves the specific area, the on-board antenna is re-aligned and the inter-satellite link is restored.

```
              .--.                      .--.                      .--.
  t1   ####-| N1 |-####  <--->  ####-| N2 |-####  <--->  ####-| N3 |-####
              \__/                      \__/                      \__/


              .--.                      .--.                      .--.
  t2   ####-| N1 |-####  <--->  ####-| N2 |-####         ####-| N3 |-####
              \__/                      \__/                      \__/


              .--.                      .--.                      .--.
  t3   ####-| N1 |-####         ####-| N2 |-####         ####-| N3 |-####
              \__/                      \__/                      \__/
```

Figure 2: Changes in connectivity between adjacent satellites in different orbits.

For any satellite in the network, the change of the connectivity failure/recovery state of the satellite links can be predicted in advance through pre-calculation. Therefore, N2 and N3 do not need to perform the flooding notification of the link state changes, and the nodes in the network can calculate the route in advance according to the predicted network topology, and timely complete the route update procedures when the topology changes.

```
                    N2-N3                N1-N2
                      |                    |
                      |--------+           |-------------+
                      |        |           |             |
                      |        |           |             |
                      |        +--------   |             +---
                      |                    |
                      +---++---++---++--   +---++---++---++--
                          t1   t2   t3         t1   t2   t3
                             Time                 Time
```

Figure 3: Inter-satellite link connectivity.

At time T1, both links between N1 and N2 and between N2 and N3 are connected, and the end-to-end path from N1 to N3 will be forwarded through N2, as shown in Figure 4. As the nodes move, the links between N1 and N2 and between N2 and N3 will predictably fail at time T3, as shown in Figure 3. In response to this predictable change in network topology, the relevant satellite nodes may perform routing calculations in advance, and the end-to-end path from N1 to N3 will be forwarded through N4, N5, N6 as shown in Figure 5.

```
                ^                      ^                      ^
                |                      |                      |
                |                      |                      |
                v  Src                 v                      v  Dst
               .--.                   .--.                   .--.
    <->  ####-| N1 |-####  <->  ####-| N2 |-####  <->  ####-| N3 |-####  <->
               \__/      ------>      \__/      ------>      \__/
                ^                      ^                      ^
                |                      |                      |
                |                      |                      |
                v                      v                      v
               .--.                   .--.                   .--.
   <---> ####-| N4 |-#### <---> ####-| N5 |-#### <---> ####-| N6 |-#### <--->
               \__/                   \__/                   \__/
                ^                      ^                      ^
                |                      |                      |             N
                |                      |                      |             ^
                v                      v                      v             |
           Orbit plane 1          Orbit plane 2          Orbit plane 3      |
                                                                            S

                                                                       Moving
                                                                    Direction
```

Figure 4: Path from N1 to N3 at T1.

```
             ^                      ^                      ^
             |                      |                      |
             |                      |                      |
             v  Src                 v                      v  Dst
            .--.                   .--.                   .--.
      ####-| N1 |-####       ####-| N2 |-####       ####-| N3 |-####
            \__/                   \__/                   \__/
             ^|                     ^                      ^^
             ||                     |                      ||
             ||                     |                      ||
             vv                     v                      |v
            .--.      ------>      .--.      ------>      .--.
<---> ####-| N4 |-#### <---> ####-| N5 |-#### <---> ####-| N6 |-#### <--->
            \__/                   \__/                   \__/
             ^                      ^                      ^
             |                      |                      |             N
             |                      |                      |             ^
             v                      v                      v             |
        Orbit plane 1          Orbit plane 2          Orbit plane 3      |
                                                                         S
                                                                    Moving
                                                                 Direction
```

Figure 5: Path from N1 to N3 at T3.

6.2. Scenario 2: Predictable property changes of satellite links

As shown in Figure 6, N1 and N2 are adjacent satellites at the same altitude and in different orbit planes, moving from the equator to the polar region from south to north. At time T1, the distance between N1 and N2 is the largest, and at time T3, the distance between N1 and N2 is the smallest. For any satellite in the network, the changes in satellite communication distances will influence the characteristics of satellite links, including delay and error rate. Each satellite in the network can predict these changes in advance through pre-calculation, and update the link cost correspondingly. Therefore, N1 and N2 do not need to perform the flooding notification of the link state changes, and the nodes in the network can calculate the route in advance according to the predicted link cost change and switch the routing path at an appropriate time.

```
           .--.                              .--.
t1   ####-| N1 |-####  <------------>  ####-| N2 |-####
           \__/                              \__/

           .--.                           .--.
t2   ####-| N1 |-####  <--------->  ####-| N2 |-####
           \__/                           \__/

           .--.                        .--.
t3   ####-| N1 |-####  <------>  ####-| N2 |-####
           \__/                        \__/
```

Figure 6: Changes of communication distance between adjacent satellites in different orbits.

At time T1, N7 and N3 are symmetrically located on both sides of the equator, and N4, N5 and N6 are located in the equatorial region. Therefore, the communication distance between N4 and N5 and between N5 and N6 is the largest, and the corresponding link cost is also higher. Therefore, the end-to-end path from N7 to N3 does not include the N4, N5, and N6, but forwards through N8, N5, and N2 which is shown in Figure 7.

```
                 ^                     ^                     ^
                 |                     |                     |
                 |                     |                     |
                 v                     v                     v  Dst
                .--.                  .--.                  .--.
     <--> ####-| N1 |-#### <--> ####-| N2 |-#### <--> ####-| N3 |-#### <-->
                \__/                  \__/                  \__/
                 ^                     ^^      ------->      ^
                 |                     ||                    |
                 |                     ||                    |
                 v                     v|                    v
                .--.                  .--.                  .--.
    <---->####-| N4 |-####<---->####-| N5 |-####<---->####-| N6 |-####<---->
                \__/                  \__/                  \__/
                 ^                     ^^                    ^
                 |                     ||                    |
                 |                     ||                    |
                 v       ------->      v|                    v
                .--.                  .--.                  .--.
     <--> ####-| N7 |-#### <--> ####-| N8 |-#### <--> ####-| N9 |-#### <-->
                \__/                  \__/                  \__/
                 ^  Src                ^                     ^
                 |                     |                     |             N
                 |                     |                     |             ^
                 v                     v                     v             |
            Orbit plane 1         Orbit plane 2         Orbit plane 3      |
                                                                           S

                                                                      Moving
                                                                   Direction
```

Figure 7: Path from N7 to N3 at T3.

With the continuous movement of the node, at time T3, the source satellite N7 and the destination satellite N3 both move across the equator and enter the northern hemisphere, while N1, N2 and N3 are in a relatively near-polar region. Therefore, the communication distance between N1, N2, and N3 is the smallest compared to other inter-satellite links, and the corresponding link cost is also lower. Thus, the end-to-end path from N7 to N3 includes N4, N1, N2 which is shown in Figure 8.

```
                ^                      ^                      ^
                |                      |                      |
                |                      |                      |
                v                      v                      v  Dst
               .--.                   .--.                   .--.
    <->  ####-| N1 |-####  <->  ####-| N2 |-####  <->  ####-| N3 |-####  <->
               \__/                   \__/                   \__/
                ^^        ---->        ^         ----->       ^
                ||                     |                      |
                ||                     |                      |
                v|                     v                      v
               .--.                   .--.                   .--.
   <---> ####-| N4 |-#### <---> ####-| N5 |-#### <---> ####-| N6 |-#### <--->
               \__/                   \__/                   \__/
                ^^                     ^                      ^
                ||                     |                      |
                ||                     |                      |
                v|                     v                      v
               .--.                   .--.                   .--.
  <----->####-| N7 |-####<----->####-| N8 |-####<----->####-| N9 |-####<----->
               \__/                   \__/                   \__/
                ^  Src                 ^                      ^
                |                      |                      |              N
                |                      |                      |              ^
                v                      v                      v              |
           Orbit plane 1          Orbit plane 2          Orbit plane 3       |
                                                                             S

                                                                        Moving
                                                                     Direction
```

Figure 8: Path from N7 to N3 at T1.

7. Security Considerations

TBA

8. Acknowledgements

TBA

9. IANA Considerations

TBA

10. Normative References

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