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Segment Routing IPv6 for Mobile User Plane
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Abstract

This document discusses the applicability of SRv6 (Segment Routing IPv6) to the user-plane of mobile networks. The network programming nature of SRv6 accomplishes mobile user-plane functions in a simple manner. The statelessness of SRv6 and its ability to control both service layer path and underlying transport can be beneficial to the mobile user-plane, providing flexibility, end-to-end network slicing, and SLA control for various applications.

This document discusses how SRv6 (Segment Routing over IPv6) could be used as user-plane of mobile networks. This document also specifies the SRv6 Segment Endpoint behaviors required for mobility use-cases.

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1. Introduction

In mobile networks, mobility systems provide connectivity over a wireless link to stationary and non-stationary nodes. The user-plane establishes a tunnel between the mobile node and its anchor node over IP-based backhaul and core networks.

This document specifies the applicability of SRv6 (Segment Routing IPv6) [RFC8754][RFC8986] to mobile networks.

Segment Routing [RFC8402] is a source routing architecture: a node steers a packet through an ordered list of instructions called "segments". A segment can represent any instruction, topological or service based.

SRv6 applied to mobile networks enables a source-routing based mobile architecture, where operators can explicitly indicate a route for the packets to and from the mobile node. The SRv6 Endpoint nodes serve as mobile user-plane anchors.

2. Conventions and Terminology

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.

2.1. Terminology

* CNF: Cloud-native Network Function
* NFV: Network Function Virtualization
* PDU: Packet Data Unit
* PDU Session: Context of a UE connected to a mobile network.
* UE: User Equipment
* gNB: gNodeB [TS.23501]
* UPF: User Plane Function
* VNF: Virtual Network Function

* DN: Data Network
* Uplink: from the UE towards the DN
* Downlink: from the DN towards the UE

The following terms used within this document are defined in [RFC8402]: Segment Routing, SR Domain, Segment ID (SID), SRv6, SRv6 SID, Active Segment, SR Policy, Prefix SID, Adjacency SID and Binding SID.

The following terms used within this document are defined in [RFC8754]: SRH, SR Source Node, Transit Node, SR Segment Endpoint Node and Reduced SRH.

The following terms used within this document are defined in [RFC8986]: NH, SL, FIB, SA, DA, SRv6 SID behavior, SRv6 Segment Endpoint Behavior.

2.2. Conventions

An SR Policy is resolved to a SID list. A SID list is represented as <S1, S2, S3> where S1 is the first SID to visit, S2 is the second SID to visit, and S3 is the last SID to visit along the SR path.

(SA,DA) (S3, S2, S1; SL) represents an IPv6 packet with:

* Source Address is SA, Destination Address is DA, and next-header is SRH
* SRH with SID list <S1, S2, S3> with Segments Left = SL
* Note the difference between the <> and () symbols: <S1, S2, S3> represents a SID list where S1 is the first SID and S3 is the last SID to traverse. (S3, S2, S1; SL) represents the same SID list but encoded in the SRH format where the rightmost SID in the SRH is the first SID and the leftmost SID in the SRH is the last SID. When referring to an SR policy in a high-level use-case, it is simpler to use the <S1, S2, S3> notation. When referring to an illustration of the detailed packet behavior, the (S3, S2, S1; SL) notation is more convenient.
* The payload of the packet is omitted.

(SA1,DA1) (SA2, DA2) represents an IPv6 packet with:

* Source Address is SA1, Destination Address is DA1, and next-header is IP
* Source Address is SA2, Destination Address is DA2.

Throughout the document the representation SRH[n] is used as shorter representation of Segment List[n], as defined in [RFC8754].

This document uses the following conventions throughout the different examples:

* gNB::1 is an IPv6 address (SID) assigned to the gNB.
* U1::1 is an IPv6 address (SID) assigned to UPF1.
* U2::1 is an IPv6 address (SID) assigned to UPF2.
* U2:: is the Locator of UPF2.

2.3. Predefined SRv6 Endpoint Behaviors

The following SRv6 Endpoint Behaviors are defined in [RFC8986].

* End.DT4: Decapsulation and Specific IPv4 Table Lookup
* End.DT6: Decapsulation and Specific IPv6 Table Lookup
* End.DT46: Decapsulation and Specific IP Table Lookup
* End.DX4: Decapsulation and IPv4 Cross-Connect
* End.DX6: Decapsulation and IPv6 Cross-Connect
* End.DX2: Decapsulation and L2 Cross-Connect
* End.T: Endpoint with specific IPv6 Table Lookup

This document defines new SRv6 Segment Endpoint Behaviors in Section 6.

3. Motivation

Mobile networks are becoming more challenging to operate. On one hand, traffic is constantly growing, and latency requirements are tighter; on the other-hand, there are new use-cases like distributed NFV Infrastructure that are also challenging network operations. On top of this, the number of devices connected is steadily growing, causing scalability problems in mobile entities as the state to maintain keeps increasing.

The current architecture of mobile networks does not take into account the underlying transport. The user-plane is rigidly fragmented into radio access, core and service networks, connected by tunneling according to user-plane roles such as access and anchor nodes. These factors have made it difficult for the operator to optimize and operate the data-path.

In the meantime, applications have shifted to use IPv6, and network operators have started adopting IPv6 as their IP transport. SRv6, the IPv6 dataplane instantiation of Segment Routing [RFC8402], integrates both the application data-path and the underlying transport layer into a single protocol, allowing operators to optimize the network in a simplified manner and removing forwarding state from the network. It is also suitable for virtualized environments, like VNF/CNF to VNF/CNF networking. SRv6 has been deployed in dozens of networks [I-D.matsushima-spring-srv6-deployment-status].

SRv6 defines the network-programming concept [RFC8986]. Applied to mobility, SRv6 can provide the user-plane behaviors needed for mobility management. SRv6 takes advantage of the underlying transport awareness and flexibility together with the ability to also include services to optimize the end-to-end mobile dataplane.

The use-cases for SRv6 mobility are discussed in [I-D.camarilloelmalky-springdmm-srv6-mob-usecases], and the architectural benefits are discussed in [I-D.kohno-dmm-srv6mob-arch].

4. 3GPP Reference Architecture

This section presents the 3GPP Reference Architecture and possible deployment scenarios.

Figure 1 shows a reference diagram from the 5G packet core architecture [TS.23501].

The user plane described in this document does not depend on any specific architecture. The 5G packet core architecture as shown is based on the 3GPP standards.

```
                                   +-----+
                                   | AMF |
                                  /+-----+
                                 /    | [N11]
                          [N2]  /  +-----+
                        +------/   | SMF |
                       /           +-----+
                      /              / \
                     /              /   \  [N4]
                    /              /     \                    _________
                   /              /       \                  /         \
+--+      +-----+ [N3] +-------+  [N9]  +-------+  [N6]     /           \
|UE|------| gNB |------| UPF1  |--------| UPF2  |---------  \    DN     /
+--+      +-----+      +-------+        +-------+            \_________/
```

Figure 1: 3GPP 5G Reference Architecture

* UE: User Equipment
* gNB: gNodeB with N3 interface towards packet core (and N2 for control plane)
* UPF1: UPF with Interfaces N3 and N9 (and N4 for control plane)
* UPF2: UPF with Interfaces N9 and N6 (and N4 for control plane)
* SMF: Session Management Function
* AMF: Access and Mobility Management Function
* DN: Data Network e.g., operator services, Internet access

This reference diagram does not depict a UPF that is only connected to N9 interfaces, although the mechanisms defined in this document also work in such a case.

Each session from a UE gets assigned to a UPF. Sometimes multiple UPFs may be used, providing richer service functions. A UE gets its IPv4 address, or IPv6 prefix, from the DHCP block of its UPF. The UPF advertises that IP address block toward the Internet, ensuring that return traffic is routed to the right UPF.

5. User-plane modes

This section introduces an SRv6 based mobile user-plane.It presents two different "modes" that vary with respect to the use of SRv6. The first one is the "Traditional mode", which inherits the current 3GPP mobile architecture. In this mode GTP-U protocol [TS.29281] is replaced by SRv6, however the N3, N9 and N6 interfaces are still point-to-point interfaces with no intermediate waypoints as in the current mobile network architecture.

The second mode is the "Enhanced mode". This is an evolution from the "Traditional mode". In this mode the N3, N9 or N6 interfaces have intermediate waypoints -SIDs- that are used for Traffic Engineering or VNF purposes transparent to 3GPP functionalities. This results in optimal end-to-end policies across the mobile network with transport and services awareness.

In both, the Traditional and the Enhanced modes, this document assumes that the gNB as well as the UPFs are SR-aware (N3, N9 and -potentially- N6 interfaces are SRv6).

In addition to those two modes, this document introduces three mechanisms for interworking with legacy access networks (those where the N3 interface is unmodified). In this document they are introduced as a variant to the Enhanced mode, however they are equally applicable to the Traditional mode.

One of these mechanisms is designed to interwork with legacy gNBs using GTP-U/IPv4. The second mechanism is designed to interwork with legacy gNBs using GTP-U/IPv6. The third of those mechanisms is another mode that allows deploying SRv6 when legacy gNBs and UPFs that still run GTP-U.

This document uses SRv6 Segment Endpoint Behaviors defined in [RFC8986] as well as new SRv6 Segment Endpoint Behaviors designed for the mobile user plane that are defined in this document in Section 6.

5.1. Traditional mode

In the traditional mode, the existing mobile UPFs remain unchanged with the sole exception of the use of SRv6 as the data plane instead of GTP-U. There is no impact to the rest of the mobile system.

In existing 3GPP mobile networks, a PDU Session is mapped 1-for-1 with a specific GTP-U tunnel (Tunnel Endpoint Identifier - TEID). This 1-for-1 mapping is mirrored here to replace GTP-U encapsulation with the SRv6 encapsulation, while not changing anything else. There will be a unique SRv6 SID associated with each PDU Session, and the SID list only contains a single SID.

The traditional mode minimizes the changes required to the mobile system; hence it is a good starting point for forming a common ground.

The gNB/UPF control-plane (N2/N4 interface) is unchanged, specifically a single IPv6 address is provided to the gNB. The same control plane signalling is used, and the gNB/UPF decides to use SRv6 based on signaled GTP-U parameters per local policy. The only information from the GTP-U parameters used for the SRv6 policy is the TEID, QFI -QoS Flow Identifier-, and the IPv6 Destination Address.

Our example topology is shown in Figure 2. The gNB and the UPFs are SR-aware. In the descriptions of the uplink and downlink packet flow, A is an IPv6 address of the UE, and Z is an IPv6 address reachable within the Data Network DN. A new SRv6 Endpoint Behavior, End.MAP, defined in Section 6.2, is used.

```
                                                              ________
                     SRv6           SRv6                     /        \
   +--+      +-----+ [N3] +-------+  [N9]  +-------+  [N6]   /          \
   |UE|------| gNB |------| UPF1  |--------| UPF2  |--------- \    DN    /
   +--+      +-----+      +-------+        +-------+           \________/
            SRv6 node     SRv6 node        SRv6 node
```

Figure 2: Traditional mode - example topology

5.1.1. Packet flow - Uplink

The uplink packet flow is as follows:

```
UE_out  : (A,Z)
gNB_out : (gNB, U1::1) (A,Z)     -> H.Encaps.Red <U1::1>
UPF1_out: (gNB, U2::1) (A,Z)     -> End.MAP
UPF2_out: (A,Z)                  -> End.DT4 or End.DT6
```

When the UE packet arrives at the gNB, the gNB performs a H.Encaps.Red operation. Since there is only one SID, there is no need to push an SRH (reduced SRH). gNB only adds an outer IPv6 header with IPv6 DA U1::1. gNB obtains the SID U1::1 from the existing control plane (N2 interface). U1::1 represents an anchoring SID specific for that session at UPF1.

When the packet arrives at UPF1, the SID U1::1 is associated with the End.MAP SRv6 Endpoint Behavior. End.MAP replaces U1::1 by U2::1, that belongs to the next UPF (U2).

When the packet arrives at UPF2, the SID U2::1 corresponds to an End.DT4/End.DT6/End.DT46 SRv6 Endpoint Behavior. UPF2 decapsulates the packet, performs a lookup in a specific table associated with that mobile network and forwards the packet toward the data network (DN).

5.1.2. Packet flow - Downlink

The downlink packet flow is as follows:

```
UPF2_in : (Z,A)
UPF2_out: (U2::, U1::2) (Z,A)    -> H.Encaps.Red <U1::2>
UPF1_out: (U2::, gNB::1) (Z,A)   -> End.MAP
gNB_out : (Z,A)                  -> End.DX4, End.DX6, End.DX2
```

When the packet arrives at the UPF2, the UPF2 maps that flow into a PDU Session. This PDU Session is associated with the segment endpoint <U1::2>. UPF2 performs a H.Encaps.Red operation, encapsulating the packet into a new IPv6 header with no SRH since there is only one SID.

Upon packet arrival on UPF1, the SID U1::2 is a local SID associated with the End.MAP SRv6 Endpoint Behavior. It maps the SID to the next anchoring point and replaces U1::2 by gNB::1, that belongs to the next hop.

Upon packet arrival on gNB, the SID gNB::1 corresponds to an End.DX4, End.DX6 or End.DX2 behavior (depending on the PDU Session Type). The gNB decapsulates the packet, removing the IPv6 header and all its extensions headers, and forwards the traffic toward the UE.

5.2. Enhanced mode

Enhanced mode improves scalability, provides traffic engineering capabilities, and allows service programming [I-D.ietf-spring-sr-service-programming], thanks to the use of multiple SIDs in the SID list (instead of a direct connectivity in between UPFs with no intermediate waypoints as in Traditional Mode).

Thus, the main difference is that the SR policy MAY include SIDs for traffic engineering and service programming in addition to the anchoring SIDs at UPFs.

Additionally in this mode the operator may choose to aggregate several devices under the same SID list (e.g., stationary residential meters [water/energy] connected to the same cell) to improve scalability.

The gNB/UPF control-plane (N2/N4 interface) is unchanged, specifically a single IPv6 address is provided to the gNB. A local policy instructs the gNB to use SRv6.

The gNB resolves the IP address received via the control plane into a SID list. The resolution mechanism is out of the scope of this document.

Note that the SIDs MAY use the arguments Args.Mob.Session (Section 6.1) if required by the UPFs.

Figure 3 shows an Enhanced mode topology. The gNB and the UPF are SR-aware. The Figure shows two service segments, S1 and C1. S1 represents a VNF in the network, and C1 represents an intermediate router used for Traffic Engineering purposes to enforce a low-latency path in the network. Note that neither S1 nor C1 are required to have an N4 interface.

```
                                    +----+  SRv6               _______
                    SRv6          --| C1 |--[N3]              /       \
   +--+    +-----+  [N3]         /  +----+  \  +------+ [N6] /         \
   |UE|----| gNB |--       SRv6 /    SRv6    --| UPF1 |------\   DN    /
   +--+    +-----+  \      [N3]/      TE       +------+       \_______/
          SRv6 node  \ +----+ /               SRv6 node
                      -| S1 |-
                       +----+
                      SRv6 node
                        VNF
```

Figure 3: Enhanced mode - Example topology

5.2.1. Packet flow - Uplink

The uplink packet flow is as follows:

```
UE_out  : (A,Z)
gNB_out : (gNB, S1)(U1::1, C1; SL=2)(A,Z)->H.Encaps.Red<S1,C1,U1::1>
S1_out  : (gNB, C1)(U1::1, C1; SL=1)(A,Z)
C1_out  : (gNB, U1::1)(A,Z)             ->End with PSP
UPF1_out: (A,Z)                         ->End.DT4,End.DT6,End.DT2U
```

UE sends its packet (A,Z) on a specific bearer to its gNB. gNB's control plane associates that session from the UE(A) with the IPv6 address B. gNB resolves B into a SID list. <S1, C1, U1::1>.

When gNB transmits the packet, it contains all the segments of the SR policy. The SR policy includes segments for traffic engineering (C1) and for service programming (S1).

Nodes S1 and C1 perform their related Endpoint functionality and forward the packet. The End with PSP functionality referes to the Endpoint behavior with Penultimate Segment Popping as defined in RFC8986.

When the packet arrives at UPF1, the active segment (U1::1) is an End.DT4/End.DT6/End.DT2U which performs the decapsulation (removing the IPv6 header with all its extension headers) and forwards toward the data network.

5.2.2. Packet flow - Downlink

The downlink packet flow is as follows:

```
UPF1_in : (Z,A)                             ->UPF1 maps the flow w/
                                              SID list <C1,S1, gNB>
UPF1_out: (U1::1, C1)(gNB::1, S1; SL=2)(Z,A)->H.Encaps.Red
C1_out  : (U1::1, S1)(gNB::1, S1; SL=1)(Z,A)
S1_out  : (U1::1, gNB::1)(Z,A)              ->End with PSP
gNB_out : (Z,A)                             ->End.DX4/End.DX6/End.DX2
```

When the packet arrives at the UPF1, the UPF1 maps that particular flow into a UE PDU Session. This UE PDU Session is associated with the policy <C1, S1, gNB>. The UPF1 performs a H.Encaps.Red operation, encapsulating the packet into a new IPv6 header with its corresponding SRH.

The nodes C1 and S1 perform their related Endpoint processing.

Once the packet arrives at the gNB, the IPv6 DA corresponds to an End.DX4, End.DX6 or End.DX2 behavior at the gNB (depending on the underlying traffic). The gNB decapsulates the packet, removing the IPv6 header, and forwards the traffic towards the UE. The SID gNB::1 is one example of a SID associated to this service.

Note that there are several means to provide the UE session aggregation. The decision on which one to use is a local decision made by the operator. One option is to use the Args.Mob.Session (Section 6.1). Another option comprises the gNB performing an IP lookup on the inner packet by using the End.DT4, End.DT6, and End.DT2U behaviors.

5.2.3. Scalability

The Enhanced Mode improves scalability since it allows the aggregation of several UEs under the same SID list. For example, in the case of stationary residential meters that are connected to the same cell, all such devices can share the same SID list. This improves scalability compared to Traditional Mode (unique SID per UE) and compared to GTP-U (TEID per UE).

5.3. Enhanced mode with unchanged gNB GTP-U behavior

This section describes two mechanisms for interworking with legacy gNBs that still use GTP-U: one for IPv4, and another for IPv6.

In the interworking scenarios as illustrated in Figure 4, the gNB does not support SRv6. The gNB supports GTP-U encapsulation over IPv4 or IPv6. To achieve interworking, an SR Gateway (SRGW) entity is added. The SRGW is a new entity that maps the GTP-U traffic into SRv6. It is deployed at the boundary of the SR Domain and performs the mapping functionality for inbound/outbound traffic.

The SRGW is not an anchor point and maintains very little state. For this reason, both IPv4 and IPv6 methods scale to millions of UEs.

```
                                                         ________
                  IP GTP-U        SRv6                  /        \
 +--+      +-----+ [N3] +-------+  [N9]  +-------+  [N6]   /          \
 |UE|------| gNB |------| SRGW |--------| UPF  |---------\    DN    /
 +--+      +-----+      +-------+        +-------+         \________/
                       SR Gateway       SRv6 node
```

Figure 4: Example topology for interworking

Both of the mechanisms described in this section are applicable to either the Traditional Mode or the Enhanced Mode.

5.3.1. Interworking with IPv6 GTP-U

In this interworking mode the gNB at the N3 interface uses GTP-U over IPv6.

Key points:

* The gNB is unchanged (control-plane or user-plane) and encapsulates into GTP-U (N3 interface is not modified).
* The 5G Control-Plane towards the gNB (N2 interface) is unmodified, though multiple UPF addresses need to be used - one IPv6 address (i.e. a BSID at the SRGW) is needed per <SLA, PDU session type>. The SRv6 SID is different depending on the required <SLA, PDU session type> combination.
* In the uplink, the SRGW removes GTP-U header, finds the SID list related to the IPv6 DA, and adds SRH with the SID list.
* There is no state for the downlink at the SRGW.
* There is simple state in the uplink at the SRGW; using Enhanced mode results in fewer SR policies on this node. An SR policy is shared across UEs as long as they belong to the same context (i.e., tenant). A set of many different policies (i.e., different SLAs) increases the amount of state required.
* When a packet from the UE leaves the gNB, it is SR-routed. This simplifies network slicing [I-D.ietf-lsr-flex-algo].
* In the uplink, the SRv6 BSID steers traffic into an SR policy when it arrives at the SRGW.

An example topology is shown in Figure 5.

S1 and C1 are two service segments. S1 represents a VNF in the network, and C1 represents a router configured for Traffic Engineering.

```
                                  +----+
                IPv6/GTP-U       -| S1 |-                             ___
   +--+  +-----+ [N3]           / +----+ \                           /
   |UE|--| gNB |-         SRv6 /   SRv6   \ +----+   +------+ [N6] /
   +--+  +-----+ \        [N9]/     VNF    -| C1 |---| UPF2 |------\  DN
           GTP-U  \ +------+ /               +----+   +------+       \___
                   -| SRGW |-                 SRv6      SRv6
                    +------+                   TE
                   SR Gateway
```

Figure 5: Enhanced mode with unchanged gNB IPv6/GTP-U behavior

5.3.1.1. Packet flow - Uplink

The uplink packet flow is as follows:

```
UE_out  : (A,Z)
gNB_out : (gNB, B)(GTP: TEID T)(A,Z)       -> Interface N3 unmodified
                                              (IPv6/GTP)
SRGW_out: (SRGW, S1)(U2::T, C1; SL=2)(A,Z) -> B is an End.M.GTP6.D
                                              SID at the SRGW
S1_out  : (SRGW, C1)(U2::T, C1; SL=1)(A,Z)
C1_out  : (SRGW, U2::T)(A,Z)               -> End with PSP
UPF2_out: (A,Z)                            -> End.DT4 or End.DT6
```

The UE sends a packet destined to Z toward the gNB on a specific bearer for that session. The gNB, which is unmodified, encapsulates the packet into IPv6, UDP, and GTP-U headers. The IPv6 DA B, and the GTP-U TEID T are the ones received in the N2 interface.

The IPv6 address that was signaled over the N2 interface for that UE PDU Session, B, is now the IPv6 DA. B is an SRv6 Binding SID at the SRGW. Hence the packet is routed to the SRGW.

When the packet arrives at the SRGW, the SRGW identifies B as an End.M.GTP6.D Binding SID (see Section 6.3). Hence, the SRGW removes the IPv6, UDP, and GTP-U headers, and pushes an IPv6 header with its own SRH containing the SIDs bound to the SR policy associated with this BindingSID. There at least one instance of the End.M.GTP6.D SID per PDU type.

S1 and C1 perform their related Endpoint functionality and forward the packet.

When the packet arrives at UPF2, the active segment is (U2::T) which is bound to End.DT4/6. UPF2 then decapsulates (removing the outer IPv6 header with all its extension headers) and forwards the packet toward the data network.

5.3.1.2. Packet flow - Downlink

The downlink packet flow is as follows:

```
UPF2_in : (Z,A)                             -> UPF2 maps the flow with
                                               <C1, S1, SRGW::TEID,gNB>
UPF2_out: (U2::1, C1)(gNB, SRGW::TEID, S1; SL=3)(Z,A) -> H.Encaps.Red
C1_out  : (U2::1, S1)(gNB, SRGW::TEID, S1; SL=2)(Z,A)
S1_out  : (U2::1, SRGW::TEID)(gNB, SRGW::TEID, S1, SL=1)(Z,A)
SRGW_out: (SRGW, gNB)(GTP: TEID=T)(Z,A)   -> SRGW/96 is End.M.GTP6.E
gNB_out : (Z,A)
```

When a packet destined to A arrives at the UPF2, the UPF2 performs a lookup in the table associated to A and finds the SID list <C1, S1, SRGW::TEID, gNB>. The UPF2 performs an H.Encaps.Red operation, encapsulating the packet into a new IPv6 header with its corresponding SRH.

C1 and S1 perform their related Endpoint processing.

Once the packet arrives at the SRGW, the SRGW identifies the active SID as an End.M.GTP6.E function. The SRGW removes the IPv6 header and all its extensions headers. The SRGW generates new IPv6, UDP, and GTP-U headers. The new IPv6 DA is the gNB which is the last SID in the received SRH. The TEID in the generated GTP-U header is an argument of the received End.M.GTP6.E SID. The SRGW pushes the headers to the packet and forwards the packet toward the gNB. There is one instance of the End.M.GTP6.E SID per PDU type.

Once the packet arrives at the gNB, the packet is a regular IPv6/GTP-U packet. The gNB looks for the specific radio bearer for that TEID and forwards it on the bearer. This gNB behavior is not modified from current and previous generations.

5.3.1.3. Scalability

For the downlink traffic, the SRGW is stateless. All the state is in the SRH pushed by the UPF2. The UPF2 must have the UE states since it is the UE’s session anchor point.

For the uplink traffic, the state at the SRGW does not necessarily need to be unique per PDU Session; the SR policy can be shared among UEs. This enables more scalable SRGW deployments compared to a solution holding millions of states, one or more per UE.

5.3.2. Interworking with IPv4 GTP-U

In this interworking mode the gNB uses GTP over IPv4 in the N3 interface

Key points:

* The gNB is unchanged and encapsulates packets into GTP-U (the N3 interface is not modified).
* N2 signaling is not changed, though multiple UPF addresses need to be provided - one for each PDU Session Type.
* In the uplink, traffic is classified by SRGW's classification engine and steered into an SR policy. The SRGW may be implemented in a UPF or as a separate entity. How the classification engine rules are set up is outside the scope of this document, though one example is using BGP signaling from a Mobile User Plane Controller [I-D.mhkk-dmm-srv6mup-architecture].
* SRGW removes GTP-U header, finds the SID list related to DA, and adds an SRH with the SID list.

An example topology is shown in Figure 6. In this mode the gNB is an unmodified gNB using IPv4/GTP. The UPFs are SR-aware. As before, the SRGW maps the IPv4/GTP-U traffic to SRv6.

S1 and C1 are two service segment endpoints. S1 represents a VNF in the network, and C1 represents a router configured for Traffic Engineering.

```
                               +----+
             IPv4/GTP-U       -| S1 |-                            ____
+--+  +-----+ [N3]           / +----+ \                          /
|UE|--| gNB |-         SRv6 /   SRv6   \ +----+   +------+ [N6] /
+--+  +-----+ \        [N9]/     VNF    -| C1 |---| UPF2 |------\  DN
        GTP-U  \ +------+ /              +----+   +------+       \____
                -| UPF1 |-                SRv6      SRv6
                 +------+                  TE
                SR Gateway
```

Figure 6: Enhanced mode with unchanged gNB IPv4/GTP-U behavior

5.3.2.1. Packet flow - Uplink

The uplink packet flow is as follows:

```
gNB_out : (gNB, B)(GTP: TEID T)(A,Z)          -> Interface N3
                                                 unchanged IPv4/GTP
SRGW_out: (SRGW, S1)(U2::1, C1; SL=2)(A,Z)    -> H.M.GTP4.D function
S1_out  : (SRGW, C1)(U2::1, C1; SL=1)(A,Z)
C1_out  : (SRGW, U2::1) (A,Z)                 -> PSP
UPF2_out: (A,Z)                               -> End.DT4 or End.DT6
```

The UE sends a packet destined to Z toward the gNB on a specific bearer for that session. The gNB, which is unmodified, encapsulates the packet into a new IPv4, UDP, and GTP-Uheaders. The IPv4 DA, B, and the GTP-UTEID are the ones received at the N2 interface.

When the packet arrives at the SRGW for UPF1, the SRGW has an classification engine rule for incoming traffic from the gNB, that steers the traffic into an SR policy by using the function H.M.GTP4.D. The SRGW removes the IPv4, UDP, and GTP headers and pushes an IPv6 header with its own SRH containing the SIDs related to the SR policy associated with this traffic. The SRGW forwards according to the new IPv6 DA.

S1 and C1 perform their related Endpoint functionality and forward the packet.

When the packet arrives at UPF2, the active segment is (U2::1) which is bound to End.DT4/6 which performs the decapsulation (removing the outer IPv6 header with all its extension headers) and forwards toward the data network.

Note that the interworking mechanisms for IPv4/GTP-U and IPv6/GTP-U differs. This is due to the fact that IPv6/GTP-U can leverage the remote steering capabilities provided by the Segment Routing BSID. In IPv4 this construct is not available, and building a similar mechanism would require a significant address consumption.

5.3.2.2. Packet flow - Downlink

The downlink packet flow is as follows:

```
UPF2_in : (Z,A)                            -> UPF2 maps flow with SID
                                            <C1, S1,GW::SA:DA:TEID>
UPF2_out: (U2::1, C1)(GW::SA:DA:TEID, S1; SL=2)(Z,A) ->H.Encaps.Red
C1_out  : (U2::1, S1)(GW::SA:DA:TEID, S1; SL=1)(Z,A)
S1_out  : (U2::1, GW::SA:DA:TEID)(Z,A)
SRGW_out: (GW, gNB)(GTP: TEID=T)(Z,A)       -> End.M.GTP4.E
gNB_out : (Z,A)
```

When a packet destined to A arrives at the UPF2, the UPF2 performs a lookup in the table associated to A and finds the SID list <C1, S1, SRGW::SA:DA:TEID>. The UPF2 performs a H.Encaps.Red operation, encapsulating the packet into a new IPv6 header with its corresponding SRH.

The nodes C1 and S1 perform their related Endpoint processing.

Once the packet arrives at the SRGW, the SRGW identifies the active SID as an End.M.GTP4.E function. The SRGW removes the IPv6 header and all its extensions headers. The SRGW generates an IPv4, UDP, and GTP-U headers. The IPv4 SA and DA are received as SID arguments. The TEID in the generated GTP-U header is also the arguments of the received End.M.GTP4.E SID. The SRGW pushes the headers to the packet and forwards the packet toward the gNB.

When the packet arrives at the gNB, the packet is a regular IPv4/GTP-U packet. The gNB looks for the specific radio bearer for that TEID and forwards it on the bearer. This gNB behavior is not modified from current and previous generations.

5.3.2.3. Scalability

For the downlink traffic, the SRGW is stateless. All the state is in the SRH pushed by the UPF2. The UPF must have this UE-base state anyway (since it is its anchor point).

For the uplink traffic, the state at the SRGW is dedicated on a per UE/session basis according to a classification engine. There is state for steering the different sessions in the form of an SR Policy. However, SR policies are shared among several UE/sessions.

5.3.3. Extensions to the interworking mechanisms

This section presents two mechanisms for interworking with gNBs and UPFs that do not support SRv6. These mechanisms are used to support GTP-U over IPv4 and IPv6.

Even though these methods are presented as an extension to the "Enhanced mode", it is straightforward in its applicability to the "Traditional mode".

5.4. SRv6 Drop-in Interworking

This section introduces another mode useful for legacy gNB and UPFs that still operate with GTP-U. This mode provides an SRv6-enabled user plane in between two GTP-U tunnel endpoints.

This mode employs two SRGWs that map GTP-U traffic to SRv6 and vice-versa.

Unlike other interworking modes, in this mode both of the mobility overlay endpoints use GTP-U. Two SRGWs are deployed in either N3 or N9 interface to realize an intermediate SR policy.

```
                            +----+
                           -| S1 |-
+-----+                   / +----+ \
| gNB |-           SRv6 /   SRv6   \ +----+   +--------+    +-----+
+-----+  \              /     VNF    -| C1 |---| SRGW-B |----| UPF |
   GTP[N3]\ +--------+ /              +----+   +--------+    +-----+
           -| SRGW-A |-                SRv6   SR Gateway-B     GTP
            +--------+                  TE
           SR Gateway-A
```

Figure 7: Example topology for SRv6 Drop-in mode

The packet flow of Figure 7 is as follows:

```
gNB_out : (gNB, U::1)(GTP: TEID T)(A,Z)
GW-A_out: (GW-A, S1)(U::1, SGB::TEID, C1; SL=3)(A,Z)->U::1 is an
                                                      End.M.GTP6.D.Di
                                                      SID at SRGW-A
S1_out  : (GW-A, C1)(U::1, SGB::TEID, C1; SL=2)(A,Z)
C1_out  : (GW-A, SGB::TEID)(U::1, SGB::TEID, C1; SL=1)(A,Z)
GW-B_out: (GW-B, U::1)(GTP: TEID T)(A,Z)            ->SGB::TEID is an
                                                      End.M.GTP6.E
                                                      SID at SRGW-B
UPF_out : (A,Z)
```

When a packet destined to Z is sent to the gNB, which is unmodified (control-plane and user-plane remain GTP-U), gNB performs encapsulation into a new IP, UDP, and GTP-U headers. The IPv6 DA, U::1, and the GTP-U TEID are the ones received at the N2 interface.

The IPv6 address that was signaled over the N2 interface for that PDU Session, U::1, is now the IPv6 DA. U::1 is an SRv6 Binding SID at SRGW-A. Hence the packet is routed to the SRGW.

When the packet arrives at SRGW-A, the SRGW identifies U::1 as an End.M.GTP6.D.Di Binding SID (see Section 6.4). Hence, the SRGW removes the IPv6, UDP, and GTP-U headers, and pushes an IPv6 header with its own SRH containing the SIDs bound to the SR policy associated with this Binding SID. There is one instance of the End.M.GTP6.D.Di SID per PDU type.

S1 and C1 perform their related Endpoint functionality and forward the packet.

Once the packet arrives at SRGW-B, the SRGW identifies the active SID as an End.M.GTP6.E function. The SRGW removes the IPv6 header and all its extensions headers. The SRGW generates new IPv6, UDP, and GTP headers. The new IPv6 DA is U::1 which is the last SID in the received SRH. The TEID in the generated GTP-U header is an argument of the received End.M.GTP6.E SID. The SRGW pushes the headers to the packet and forwards the packet toward UPF. There is one instance of the End.M.GTP6.E SID per PDU type.

Once the packet arrives at UPF, the packet is a regular IPv6/GTP packet. The UPF looks for the specific rule for that TEID to forward the packet. This UPF behavior is not modified from current and previous generations.

6. SRv6 Segment Endpoint Mobility Behaviors

This section introduces new SRv6 Segment Endpoint Behaviors for the mobile user-plane. The behaviors described in this document are compatible with the NEXT and REPLACE flavors defined in [I-D.ietf-spring-srv6-srh-compression].

6.1. Args.Mob.Session

Args.Mob.Session provide per-session information for charging, buffering or other purposes required by some mobile nodes. The Args.Mob.Session argument format is used in combination with End.Map, End.DT4/End.DT6/End.DT46 and End.DX4/End.DX6/End.DX2 behaviors. Note that proposed format is applicable for 5G networks, while similar formats could be used for legacy networks.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   QFI     |R|U|                PDU Session ID                 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|PDU Sess(cont')|
+-+-+-+-+-+-+-+-+
```

Figure 8: Args.Mob.Session format

* QFI: QoS Flow Identifier [TS.38415]
* R: Reflective QoS Indication [TS.23501]. This parameter indicates the activation of reflective QoS towards the UE for the transferred packet. Reflective QoS enables the UE to map UL User Plane traffic to QoS Flows without SMF provided QoS rules.

* U: Unused and for future use. MUST be 0 on transmission and ignored on receipt.
* PDU Session ID: Identifier of PDU Session. The GTP-U equivalent is TEID.

Args.Mob.Session is required in case that one SID aggregates multiple PDU Sessions. Since the SRv6 SID is likely NOT to be instantiated per PDU session, Args.Mob.Session helps the UPF to perform the behaviors which require per QFI and/or per PDU Session granularity.

Note that the encoding of user-plane messages (e.g., Echo Request, Echo Reply, Error Indication and End Marker) is out of the scope of this draft. [I-D.murakami-dmm-user-plane-message-encoding] defines one possible encoding.

6.2. End.MAP

The "Endpoint behavior with SID mapping" behavior (End.MAP for short) is used in several scenarios. Particularly in mobility, End.MAP is used by the intermediate UPFs.

When node N receives a packet whose IPv6 DA is D and D is a local End.MAP SID, N does:

```
S01. If (IPv6 Hop Limit <= 1) {
S02.    Send an ICMP Time Exceeded message to the Source Address,
            Code 0 (Hop limit exceeded in transit),
            interrupt packet processing, and discard the packet.
S03. }
S04. Decrement IPv6 Hop Limit by 1
S05. Update the IPv6 DA with the new mapped SID
S06. Submit the packet to the egress IPv6 FIB lookup for
        transmission to the new destination
```

Notes: The SRH is not modified (neither the SID, nor the SL value).

6.3. End.M.GTP6.D

The "Endpoint behavior with IPv6/GTP-U decapsulation into SR policy" behavior (End.M.GTP6.D for short) is used in interworking scenario for the uplink towards SRGW from the legacy gNB using IPv6/GTP. Any SID instance of this behavior is associated with an SR Policy B and an IPv6 Source Address S.

When the SR Gateway node N receives a packet destined to D and D is a local End.M.GTP6.D SID, N does:

```
S01. When an SRH is processed {
S02.   If (Segments Left != 0) {
S03.      Send an ICMP Parameter Problem to the Source Address,
             Code 0 (Erroneous header field encountered),
             Pointer set to the Segments Left field,
             interrupt packet processing, and discard the packet.
S04.   }
S05.   Proceed to process the next header in the packet
S06. }
```

When processing the Upper-layer header of a packet matching a FIB entry locally instantiated as an End.M.GTP6.D SID, N does:

```
S01. If (Next Header (NH) == UDP & UDP_Dest_port == GTP) {
S02.    Copy the GTP-U TEID and QFI to buffer memory
S03.    Pop the IPv6, UDP, and GTP-U Headers
S04.    Push a new IPv6 header with its own SRH containing B
S05.    Set the outer IPv6 SA to S
S06.    Set the outer IPv6 DA to the first SID of B
S07.    Set the outer Payload Length, Traffic Class, Flow Label,
           Hop Limit, and Next-Header (NH) fields
S08.    Write in the SRH[0] the Args.Mob.Session based on
           the information of buffer memory
S09.    Submit the packet to the egress IPv6 FIB lookup and
           transmission to the new destination
S10. } Else {
S11.    Process as per [RFC8986] Section 4.1.1
S12. }
```

Notes: S07. The NH is set based on the SID parameter. There is one instantiation of the End.M.GTP6.D SID per PDU Session Type, hence the NH is already known in advance. For the IPv4v6 PDU Session Type, in addition the router inspects the first nibble of the PDU to know the NH value.

The last segment SHOULD be followed by an Args.Mob.Session argument space which is used to provide the session identifiers, as shown in line S08.

6.4. End.M.GTP6.D.Di

The "Endpoint behavior with IPv6/GTP-U decapsulation into SR policy for Drop-in Mode" behavior (End.M.GTP6.D.Di for short) is used in SRv6 drop-in interworking scenario described in Section 5.4. The difference between End.M.GTP6.D as another variant of IPv6/GTP decapsulation function is that the original IPv6 DA of the GTP-U packet is preserved as the last SID in SRH.

Any SID instance of this behavior is associated with an SR Policy B and an IPv6 Source Address S.

When the SR Gateway node N receives a packet destined to D and D is a local End.M.GTP6.D.Di SID, N does:

```
S01. When an SRH is processed {
S02.   If (Segments Left != 0) {
S03.      Send an ICMP Parameter Problem to the Source Address,
             Code 0 (Erroneous header field encountered),
             Pointer set to the Segments Left field,
             interrupt packet processing, and discard the packet.
S04.   }
S05.   Proceed to process the next header in the packet
S06. }
```

When processing the Upper-layer header of a packet matching a FIB entry locally instantiated as an End.M.GTP6.Di SID, N does:

```
S01. If (Next Header = UDP & UDP_Dest_port = GTP) {
S02.    Copy D to buffer memory
S03.    Pop the IPv6, UDP, and GTP-U Headers
S04.    Push a new IPv6 header with its own SRH containing B
S05.    Set the outer IPv6 SA to S
S06.    Set the outer IPv6 DA to the first SID of B
S07.    Set the outer Payload Length, Traffic Class, Flow Label,
           Hop Limit, and Next-Header fields
S08.    Prepend D to the SRH (as SRH[0]) and set SL accordingly
S09.    Submit the packet to the egress IPv6 FIB lookup and
           transmission to the new destination
S10. } Else {
S11.    Process as per [RFC8986] Section 4.1.1
S12. }
```

Notes: S07. The NH is set based on the SID parameter. There is one instantiation of the End.M.GTP6.Di SID per PDU Session Type, hence the NH is already known in advance. For the IPv4v6 PDU Session Type, in addition the router inspects the first nibble of the PDU to know the NH value.

S SHOULD be an End.M.GTP6.E SID instantiated at the SR gateway.

6.5. End.M.GTP6.E

The "Endpoint behavior with encapsulation for IPv6/GTP-U tunnel" behavior (End.M.GTP6.E for short) is used among others in the interworking scenario for the downlink toward the legacy gNB using IPv6/GTP.

The prefix of End.M.GTP6.E SID MUST be followed by the Args.Mob.Session argument space which is used to provide the session identifiers.

When the SR Gateway node N receives a packet destined to D, and D is a local End.M.GTP6.E SID, N does the following:

```
S01. When an SRH is processed {
S02.   If (Segments Left != 1) {
S03.      Send an ICMP Parameter Problem to the Source Address,
             Code 0 (Erroneous header field encountered),
             Pointer set to the Segments Left field,
             interrupt packet processing, and discard the packet.
S04.   }
S05.   Proceed to process the next header in the packet
S06. }
```

When processing the Upper-layer header of a packet matching a FIB entry locally instantiated as an End.M.GTP6.E SID, N does:

```
S01.    Copy SRH[0] and D to buffer memory
S02.    Pop the IPv6 header and all its extension headers
S03.    Push a new IPv6 header with a UDP/GTP-U Header
S04.    Set the outer IPv6 SA to S
S05.    Set the outer IPv6 DA from buffer memory
S06.    Set the outer Payload Length, Traffic Class, Flow Label,
           Hop Limit, and Next-Header fields
S07.    Set the GTP-U TEID (from buffer memory)
S08.    Submit the packet to the egress IPv6 FIB lookup and
           transmission to the new destination
```

Notes: An End.M.GTP6.E SID MUST always be the penultimate SID. The TEID is extracted from the argument space of the current SID.

The source address S SHOULD be an End.M.GTP6.D SID instantiated at the egress SR gateway.

6.6. End.M.GTP4.E

The "Endpoint behavior with encapsulation for IPv4/GTP-U tunnel" behavior (End.M.GTP4.E for short) is used in the downlink when doing interworking with legacy gNB using IPv4/GTP.

When the SR Gateway node N receives a packet destined to S and S is a local End.M.GTP4.E SID, N does:

```
S01. When an SRH is processed {
S02.   If (Segments Left != 0) {
S03.      Send an ICMP Parameter Problem to the Source Address,
             Code 0 (Erroneous header field encountered),
             Pointer set to the Segments Left field,
             interrupt packet processing, and discard the packet.
S04.   }
S05.   Proceed to process the next header in the packet
S06. }
```

When processing the Upper-layer header of a packet matching a FIB entry locally instantiated as an End.M.GTP4.E SID, N does:

```
S01.    Store the IPv6 DA and SA in buffer memory
S02.    Pop the IPv6 header and all its extension headers
S03.    Push a new IPv4 header with a UDP/GTP-U Header
S04.    Set the outer IPv4 SA and DA (from buffer memory)
S05.    Set the outer Total Length, DSCP, Time To Live, and
           Next-Header fields
S06.    Set the GTP-U TEID (from buffer memory)
S07.    Submit the packet to the egress IPv4 FIB lookup and
           transmission to the new destination
```

Notes: The End.M.GTP4.E SID in S has the following format:

```
 0                                                         127
 +-----------------------+-------+----------------+---------+
 |  SRGW-IPv6-LOC-FUNC   |IPv4DA |Args.Mob.Session|0 Padded |
 +-----------------------+-------+----------------+---------+
        128-a-b-c            a            b           c
```

Figure 9: End.M.GTP4.E SID Encoding

The IPv6 Source Address has the following format:

```
 0                                                         127
 +----------------------+--------+--------------------------+
 |  Source UPF Prefix   |IPv4 SA | any bit pattern(ignored) |
 +----------------------+--------+--------------------------+
          128-a-b            a                  b
```

Figure 10: IPv6 SA Encoding for End.M.GTP4.E

6.7. H.M.GTP4.D

The "SR Policy Headend with tunnel decapsulation and map to an SRv6 policy" behavior (H.M.GTP4.D for short) is used in the direction from legacy IPv4 user-plane to SRv6 user-plane network.

When the SR Gateway node N receives a packet destined to a SRGW-IPv4-Prefix, N does:

```
S01. IF Payload == UDP/GTP-U THEN
S02.    Pop the outer IPv4 header and UDP/GTP-U headers
S03.    Copy IPv4 DA, TEID to form SID B
S04.    Copy IPv4 SA to form IPv6 SA B'
S05.    Encapsulate the packet into a new IPv6 header
S06.    Set the IPv6 DA = B
S07.    Forward along the shortest path to B
S08. ELSE
S09.    Drop the packet
```

The SID B has the following format:

```
0                                                         127
+-----------------------+-------+----------------+---------+
|Destination UPF Prefix |IPv4DA |Args.Mob.Session|0 Padded |
+-----------------------+-------+----------------+---------+
       128-a-b-c            a            b           c
```

Figure 11: H.M.GTP4.D SID Encoding

The SID B MAY be an SRv6 Binding SID instantiated at the first UPF (U1) to bind an SR policy [RFC9256].

6.8. End.Limit: Rate Limiting behavior

The mobile user-plane requires a rate-limit feature. For this purpose, this document defines a new behavior "End.Limit". The "End.Limit" behavior encodes in its arguments the rate limiting parameter that should be applied to this packet. Multiple flows of packets should have the same group identifier in the SID when those flows are in the same AMBR (Aggregate Maximum Bit Rate) group. The encoding format of the rate limit segment SID is as follows:

```
+----------------------+----------+-----------+
| LOC+FUNC rate-limit  | group-id | limit-rate|
+----------------------+----------+-----------+
      128-i-j                i          j
```

Figure 12: End.Limit: Rate limiting behavior argument format

If the limit-rate bits are set to zero, the node should not do rate limiting unless static configuration or control-plane sets the limit rate associated to the SID.

7. SRv6 supported 3GPP PDU session types

The 3GPP [TS.23501] defines the following PDU session types:

* IPv4
* IPv6
* IPv4v6
* Ethernet
* Unstructured

SRv6 supports the 3GPP PDU session types without any protocol overhead by using the corresponding SRv6 behaviors (End.DX4, End.DT4 for IPv4 PDU sessions; End.DX6, End.DT6, End.T for IPv6 PDU sessions; End.DT46 for IPv4v6 PDU sessions; End.DX2 for L2 and Unstructured PDU sessions).

8. Network Slicing Considerations

A mobile network may be required to implement "network slices", which logically separate network resources within the same SR Domain.

[RFC9256] describes a solution to build basic network slices with SR. Depending on the requirements, these slices can be further refined by adopting the mechanisms from:

* IGP Flex-Algo [I-D.ietf-lsr-flex-algo]
* Inter-Domain policies [RFC9087]

Furthermore, these can be combined with ODN/AS (On Demand Nexthop/ Automated Steering) [RFC9256] for automated slice provisioning and traffic steering.

Further details on how these tools can be used to create end to end network slices are documented in [I-D.ali-spring-network-slicing-building-blocks].

9. Control Plane Considerations

This document focuses on user-plane behavior and its independence from the control plane. While the SRv6 mobile user-plane behaviors may be utilized in emerging architectures, such as [I-D.gundavelli-dmm-mfa], [I-D.mhkk-dmm-srv6mup-architecture] for example, require control plane support for the user-plane, this document does not impose any change to the existent mobility control plane.

Section 11 allocates SRv6 Segment Endpoint Behavior codepoints for the new behaviors defined in this document.

10. Security Considerations

The security considerations for Segment Routing are discussed in [RFC8402]. More specifically for SRv6 the security considerations and the mechanisms for securing an SR domain are discussed in [RFC8754]. Together, they describe the required security mechanisms that allow establishment of an SR domain of trust to operate SRv6-based services for internal traffic while preventing any external traffic from accessing or exploiting the SRv6-based services.

The technology described in this document is applied to a mobile network that is within the SR Domain. It's important to note the ressemblance between the SR Domain and the 3GPP Packet Core Domain.

This document introduces new SRv6 Endpoint Behaviors. Those behaviors operate on control plane information, including information within the received SRH payload on which the behaviors operate. Altering the behaviors requires that an attacker alter the SR Domain as defined in [RFC8754]. Those behaviors do not need any special security consideration given that it is deployed within that SR Domain.

11. IANA Considerations

The following values have been allocated within the "SRv6 Endpoint Behaviors" [RFC8986] sub-registry belonging to the top-level "Segment Routing Parameters" registry:

Value	Hex	Endpoint behavior	Reference	Change Controller
40	0x0028	End.MAP	[This.ID]	IETF
41	0x0029	End.Limit	[This.ID]	IETF
69	0x0045	End.M.GTP6.D	[This.ID]	IETF
70	0x0046	End.M.GTP6.Di	[This.ID]	IETF
71	0x0047	End.M.GTP6.E	[This.ID]	IETF
72	0x0048	End.M.GTP4.E	[This.ID]	IETF

Table 1: SRv6 Mobile User-plane Endpoint Behavior Types

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Appendix A. Implementations

RFC Editor: Please remove this section prior to publication.

This document introduces new SRv6 Endpoint Behaviors. These behaviors have an open-source P4 implementation available in https://github.com/ebiken/p4srv6.

Additionally, a full open-source implementation of this document is available in Linux Foundation FD.io VPP project since release 20.05. More information available here: https://docs.fd.io/vpp/20.05/d7/d3c/srv6_mobile_plugin_doc.html.

There are also experimental implementations in M-CORD NGIC and Open Air Interface (OAI).

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Mobility-aware Transport Network Slicing for 5G
draft-ietf-dmm-tn-aware-mobility-24

Abstract

Network slicing in 5G enables logical networks for communication services of multiple 5G customers to be multiplexed over the same infrastructure. While 5G slicing covers logical separation of various aspects of 5G infrastructure and services, user’s data plane packets over the Radio Access Network (RAN) and Core Network (5GC) use IP in many segments of an end-to-end 5G slice. When end-to-end slices in a 5G System use network resources, they are mapped to corresponding Transport Network (TN) slice(s) which in turn provide the bandwidth, latency, isolation, and other criteria required for the realization of a 5G slice.

This document describes mapping of 5G slices to TN slices using UDP source port number of the GTP-U bearer when the TN slice provider is separated by an "attachment circuit" from the networks in which the 5G network functions are deployed, for example, 5G functions that are distributed across data centers. The slice mapping defined here is supported transparently when a 5G user device moves across 5G attachment points and session anchors.

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1. Introduction

3GPP architecture for 5G System (5GS) in [TS.23.501-3GPP], [TS.23.502-3GPP] and [TS.23.503-3GPP] for 5GC (5G Core), and the NG-RAN architecture defined in [TS.38.300-3GPP] and [TS.38.401-3GPP] describe slicing as one of the capabilities for the communication services that 5G systems provide. Slice types defined by the 3GPP include enhanced mobile broadband (eMBB) communications, ultra-reliable low latency communications (URLLC), massive internet of things (MIoT) and vehicle-to-X (V2X) and high-performance machine type communications (HMTC). The slice types list is exemplary and other slice types can be defined in future.

5G network slicing is defined by the 3GPP [TS.28.530-3GPP] as an approach, "where logical networks/partitions are created, with appropriate isolation, resources, and optimized topology to serve a purpose or service category (e.g. use case/traffic category, or for MNO internal reasons) or customers logical system created "on-demand". A 5G slice instance requested by an end-user is realized by a 5G network slice subnet (NSS) which is a collection of network functions across RAN and 5GC that make up the 5G slice. However, the capabilities of TN slices and slice characteristics for QoS, hard /soft isolation, protection and other aspects are out of scope of 3GPP standards.

TN slices in this document can be used to realize slices between 3GPP control plane NFs or for a UE's user plane. For realizing control plane slicing, the TN slice is deployed along the interface between two 3GPP NFs and this is not considered further in this document. User plane 5G slice for each user's Protocol Data Unit (PDU) session is mapped to corresponding TN slices and is the focus of this document. A PDU session in 5G is a logical connection that provides a path between a User Equipment (UE) and a data network such as the internet. Since the 3GPP Single Network Slice Selection Assistance Information (S-NSSAI) is not visible to TNs, the source UDP port number of the GTP-U (or UDP encapsulated GTP) bearer is used to convey a mapping to the TN slices on each 3GPP interface (i.e., F-U, N3, N9). Following UE handover, the S-NSSAI is mapped seamlessly to the corresponding GTP-U (or UDP encapsulated GTP) source port number of the newly attached network and can be considered to be "mobility aware". Mapping a 3GPP slice to a TN slice using GTP-U (UDP) source port number is useful when the 3GPP network function and PE for TN slice are in different IP subnets. Slice mapping using UDP source port numbers may be used in TN of public or private 3GPP networks.

A TN slice across 3GPP interfaces may use multiple technologies or network providers. In practice, the orchestration and architecture may not be monolithic or uniform. For example, there may be distinct connectivity domains including Data Centers, Public Cloud, Wide Area Networks, and different orchestration entities. Several network scenarios and mechanisms to map 3GPP and IETF network slices are found in [I-D.ietf-teas-5g-network-slice-application] and [I-D.ietf-teas-5g-ns-ip-mpls]. Unlike mapping of a fronthaul 3GPP slice to a TN slice, TN slice(s) for 3GPP backhaul (F1-U/N3/N9) corresponds to slice characteristics of the UE session during initial setup (user initiates 3GPP connectivity session) and following UE mobility. For example, a UE served by the 3GPP system for high throughput, low latency service and related 3GPP slice should be mapped to a TN slice that provides the corresponding characteristics even after handover. This document defines a mechanism where the source UDP port number of a layer 3 GTP bearer (or UDP encapsulated GTP) is used to map a 3GPP slice to the TN slice at the Provider Edge (PE). 3GPP slice management ([TS.28.541-3GPP]), Attachment Circuit (AC) in [RFC9834] YANG model for UDP tunnel bearer in [I-D.jlu-dmm-udp-tunnel-acaas] provide the basis for the necessary mapping. It is not the purpose of this document to standardize or constrain the implementation of slicing or user plane functionality in 3GPP.

This document describes a potential way to map user plane packets of a 3GPP PDU session identified by a 3GPP slice (S-NSSAI) to an IETF Network Slice Service as defined in [RFC9543]. Section 2 provides an overview on how IP transport slices apply in a 3GPP context. Section 3 describes how to map a 3GPP slice to a TN slice at a provider edge. UDP source port ranges in TN underlays for slice mapping is described in Section 4.

2. Scope of Transport Networks in 5G Slicing

3GPP [TS.28.530-3GPP] discusses TN in the context of network slice subnets, but does not specify further details. This section provides an overview of the processes to provision and map 5G slices in backhaul and mid-haul network segments with GTP-U (UDP) source port number.

```
                      5G Control and Management Planes
    +------------------------------------------------------------------+
    | +---------------------------------------------------------------+|
    | |              5G E2E Network Slice Orchestrator                ||
    | +---+-------------+-------------+---------------+-----------+---+|
    |     |             |             |               |           |    |
    | +---+--+          |   F1-C +----+-----+         |   N2 +----+---+|
    | |      |----------(--------|gNB-CU(CP)|---------(------| 5GC CP ||
    | |      |          |        +----+-----+         |      +----+---+|
    +-|      |----------|-------------|---------------|-----------|----+
      |      |          |             |               |           |
      |      |      +---V---+         |           +---V---+       |
      |      |      | IETF  |         |           | IETF  |       |
      |gNB-DU|      |  NSC  |         E1          |  NSC  |       |
      |      |      +---+---+         |           +---+---+       |
      |      |          |             |               |           |
      |      |       __ V__           |             ___V__        |
      |      |    __/       \__     +--+---+     __/       \__    +-+-+
      |      |   /   IP/L2    \    | gNB  |   /      IP      \   |   |
   UE-+      +-(PE) Mid-haul (PE)--+CU(UP)+--(PE) Backhaul(PE)--+UPF+-DN
      +------+   \__          __/    +------+    \__          __/   +---+
                    \______/                          \______/

              |------ F1-U ------|        |----- N3 or N9 -----|
```

Figure 1: Backhaul and Mid-haul Transport Network for 5G

Figure 1 depicts a 5G System (5GS) in which a gNB is split into a gNB-CU-CP, multiple gNB-CU-UPs and multiple gNB-DUs, as described in [TS.38.401-3GPP]. In addition, the figure is expanded to show the IP transport and PE (Provider Edge) providing IP transport service to 5GS user plane entities 5G-AN (e.g., gNB) and UPF. Each PE hosts the Service Demarcation Points (SDPs) to the TN slice provider. The IETF Network Slice Controller (NSC) interfaces with the 3GPP network (customer network) that requests for TN slices (IETF network slice). The 5G management plane in turn requests the Network Slice Controller (NSC) to setup resources and connectivity for the network slice as defined in [RFC9543]. 5G E2E network slice orchestration [TS.28.533-3GPP] is used to manage the life cycle of 5G E2E network slice across RAN, TN and core network.

In this architecture, end-to-end user plane connectivity between the UE and a specific Data Network (DN) is supported by the F1-U interface (between gNB-DU and gNB-CU-UP), the N3 interface between the gNB-CU-UP and the UPF, and the N9 interface between UPFs in the core network. Over these interfaces, GTP-U is used to transport UE PDUs (IPv4, IPv6, IPv4v6, Ethernet or Unstructured) as specified in [TS.29.281-3GPP]. Data in each user’s PDU session is mapped to corresponding TN slices across N3/N9/F1-U interfaces based on the 5G slice requirements. Multiple UEs traffic (e.g., eMBB) at a location that have the same requirements may use a TN slice. 3GPP network functions (i.e., gNB-DU, gNB-CU and UPF) may however be distributed (e.g., across multiple data centers) and therefore require multiple TN slices across the respective interfaces. The TN PE does not consider 5QI in the DSCP or GTP-U header for mapping the 5G slice. 3GPP QoS with 5QI and corresponding DSCP mapping can be applied to traffic flows in PDU sessions in the slice independently. Mapping a 3GPP slice to a TN slice using GTP-U (UDP) source port number is described in Section 3.3.

The gNB-DU can also be split into two entities (O-RU and O-DU) as defined by O-RAN Alliance and therefore the user plane includes the fronthaul interface between O-RU and O-DU. However, as this interface does not rely on GTP-U to transport UE PDU, the fronthaul interface is out of scope of this document. Mid-haul and backhaul are described further in Section 3.1.

3. Mapping 3GPP Slice to Transport Network Slices

3.1. Mid-haul and Backhaul Transport Networks

As described in Figure 1, 3GPP functions gNB-CU (user plane) and gNB-DU may be distributed and have a mid-haul transport between the two 3GPP network functions. If an IP based mid-haul interface is used, the network slice instance (NSI) information can be MPLS, SRv6 based as defined in [TS.28.541-3GPP]. However, if the 3GPP network function (slice customer) is physically separated from the TN slice provider (e.g., a gNB-CU (user plane) with baseband units deployed in a data center), the MPLS, SRv6 information may not be practical to carry across to the separated TN slice provider. In this case, the source UDP port number of the GTP-U can be used to indicate the slice in the TN slice provider.

The backhaul transport over which the protocols for N3 and N9 interfaces run are described in [TS.23.501-3GPP] and [TS.23.502-3GPP]. The PDU session is carried over the radio network, and GTP-U transport protocol across N3 and N9 interfaces to the data network. GTP-U between the 3GPP network functions (gNB, UPF) serves as an overlay protocol across one or more MPLS, SRv6 or Ethernet TNs in between. During UE session setup, a number of parameters for context management are configured in the gNB, UPF and that includes network slice (S-NSSAI). On an Ethernet based backhaul interface, the slice information is carried in the Ethernet header through the VLAN tags. If an IP based backhaul interface is used, the network slice instance (NSI) information can be MPLS, SRv6 based as defined in [TS.28.541-3GPP]. However, if the 3GPP network function (slice customer) is physically separated from the TN slice provider (e.g., a gNB-CU (user plane) or UPF, or both are deployed in a data center), the MPLS, SRv6 information may not be practical to carry across to the separated TN slice provider. In this case, the source UDP port number of the GTP-U can be used to indicate the slice in the TN slice provider.

3.2. 3GPP Slice Configuration Overview

Communication services in 3GPP and the concepts to provision and manage it are described in [TS.28.530-3GPP]. A brief overview is given here with the intent to describe how it is related to an IP transport slice and the mapping between it and the 3GPP slice. Communication services (e.g., an eMBB service) may be realized in a 3GPP network using one or more slices identified by NSSAI (Network Slice Selection Assistance Information) in the 3GPP control plane signaling. In the 3GPP management plane, the network slice identified by NSSAI is realized in a Network Slice Subnet (NSS). For example, a slice S-NSSAI is available to a user at different locations (and even PLMNs) and maybe realized in an NSS at that location. An NSS consists of sets of functions from 5GC and RAN that belong to the NSS. Network interfaces of functions in an NSS may be associated to one or more slice subnets. These relationships are illustrated in Figure 2. From the viewpoint of IP transport slicing and mapping to 3GPP slices, an TN slice is associated to 3GPP core or RAN network functions in a 3GPP Network Slice Subnet (NSS). Thus, it can represent a slice of a transport path for a tenant between two 3GPP user plane functions.

```
   +--------------------+   +--------------------+   +-------------------+
   |  Comm. Service A   |   |  Comm. Service B   |   |  Comm. Service C |
   +-------+------------+   +----------+---------+   +---------+---------+
           |                           |                        \
           |                           |                         \
   +-------+-------+          +--------+------+        +--------+-------+
   |NSSAI=0x02:0x0A|          |NSSAI=0x01:0x00|        |NSSAI=0x03:0x0C|
   +-------^-------+          +-------^-------+        +---------^------+
          /                          /                           |
   ______/_______           ________/______             _______|_______
   \  Net.Slice \           \  Net.Slice \              | Net.Slice     |
    \  Subnet-A  \           \  Subnet-B  \             | Subnet-C      |
     \ (NSS-A)    \           \   (NSS-B)  \            |   (NSS-C)     |
      \            \           \            \           |               |
       \  +---------+\          \  +---------+\         |  +---------+  |
        \ |NSSI=CN1| \           \ |NSSI=CN1| \         |  |NSSI=CN3|   |
         \+-----\--+  \           \+---\----+  \        |  +---|----+   |
          \      \     \           \    \       \       |      |        |
           \  +===\====+\           \ +==\=====+ \      |  +===|====+   |
            \ |NS = TS1| \           \|NS = TS2|  \     |  |NS = TS3|   |
             \+====\===+  \           +====\===+   \    |  +===|====+   |
              \     \      \           \    \       \   |      |        |
               \  +--\-----+\       +---------\-----------+      |        |
                \ |NSSI=AN1| \      \    \ +--\-----+ \          |        |
                 \+--------+  \      \    \|NSSI=AN2+------------+        |
                  \____________\      \    +--------+   \                 |
                                        +----\------------\-------------+
                                               +------------+
```

Figure 2: Slice Configuration

Figure 2 shows the slice hierarchy described in [TS.28.530-3GPP] with 3 communication services enhanced to show the IP transport slice instances (TS1, TS2, TS3). NSSAI consists of an 8 bit Slice/Service Type (SST) and a 24 bit Slice Differentiator (SD) and is represented in Figure 2 as SST(8):SD(24). As an example, when a UE registers with 5GC with NSSAI 0x02:0x0A, 0x01:0x00, 0x03:0x0C or others, 5GC may allow NSSAI 0x01:0x00 in list of NSSAI for the UE based on the request from the UE and other factors in the network. Another factor in selecting the NSSAI is whether the UE may move to another location during the lifetime of the session. In this case, the NSSAI should be such that it has a mapping to TN slice during initial attach, and following handover. For example, a UE that attaches to 5GC with S-NSSAI = 0x01:0x00 and served by user plane instances CN1 and AN2 uses TN slice NS = TS2 to provide the resources in the IP network that corresponds to the UE session. Following handover with S-NSSAI = 0x01:0x00, the UE may be served by user plane instances CN1' and AN2' over an IP slice TS2' in the new location.

3.3. Slice Mapping using UDP Source Port Number

When a 3GPP user plane function (5G-AN, UPF) and IP transport PE are on different nodes or separated across a network, the PE router needs to have the means by which to classify the IP packet from 3GPP entity based on some header information. In [RFC9543] terminology, this is a scenario where there is an AC between the 3GPP entity (customer edge) and the SDP (Service Demarcation Point) in the TN (provider edge). The AC is provisioned between a 3GPP user plane node (i.e., gNB, UPF) in, for example, a data center, to a PE router that serves as the service demarcation point for the TN slice. The following paragraphs provide an outline of operations in a 5G system prior to PDU session setup, and during PDU session setup in mapping 3GPP slice to IETF transport slice. It should be noted that outlines of 3GPP procedures below and data structures in Figure 3 are only to illustrate the concepts in the use of YANG model extensions for layer 3 GTP bearers in [I-D.jlu-dmm-udp-tunnel-acaas]. It is not the purpose of this document to standardize or otherwise constrain the implementation of slicing and user plane functionality in 3GPP.

Prior to PDU session setup, the TN and 3GPP user plane nodes are provisioned with the necessary information for mapping the slices. The PE router in TN is provisioned to map all packets arriving on a layer 3 attachment circuit (the outer header carrying the GTP-U tunnel), i.e., a UDP source port number/range to corresponding [RFC9543] slice characteristics as shown in Section 4. 3GPP user plane nodes (gNB, UPF) are provisioned with GTP transport interface information parameters in [TS.28.541-3GPP]. Each EP_Transport (a logical transport interface in 5G user plane entities) is configured with an ATTACHMENT_CIRCUIT containing UDP source port number/range for each of the slices (S-NSSAI) supported by the 3GPP user plane node. "ATTACHMENT_CIRCUIT" is one of the enumerated options in connectionPointId (externalEndPointRefList) attribute in EP_Transport. The YANG model for the layer 3 GTP bearer (UDP tunnel with source port number/range) is defined in [I-D.jlu-dmm-udp-tunnel-acaas] and inherits the attachment circuit in [RFC9834].

During PDU session setup, the 5G control plane configures parameters to setup the user plane for the UE's PDU session across F1-U, N3 and N9 interfaces. One of parameters configured by the 5G control plane is the S-NSSAI. Data packets of the PDU session can be associated to the EP_Transport /S-NSSAI configured in the user plane entities for forwarding. The ATTACHMENT_CIRCUIT for the per S-NSSAI EP_Transport interface has UDP source port number/range which is used when forwarding a GTP-U packet belonging to the PDU session. The 3GPP user plane node can now associate the provisioned slice and EP_transport to the S-NSSAI signaled for the PDU session.

An example is shown in Figure 3.

```
                            upstream GTP-U packet
                      =====================================>

        customer edge     attachment       slice provider  customer edge
                          circuit "ac1"       _______
       +-------------+      _______        __/       \__   +-----------+
       |   gNB-CU    |   __/       \__    /     IP      \  |    UPF    |
       |N3 IP i/f =  +--/ Data Center\--(PE) Backhaul (PE)-+N3 IP i/f =|
       |  gNB-AN2-if |  \__ Network__/    \__        __/   |UPF-CN1-if |
       +--------\----+     \_______/         \____\__/     +-----------+
                 \                                 \
                  \                                +-------------------+
    +--------------\-----------------+             |   Slice Mapping:  |
    |+---------------------------+   |             |Match:             |
    ||3GPP CP Config:            |   |             |    vlan-id  = 100 |
    ||NSSI  = AN2                |   |             |    src-port = 5678|
    |+---------------------------+   |             |Action:            |
    |+------------------------------+|             |   select NS = TS2 |
    ||Slice Mapping to UPF-CN1-if:  ||             +-------------------+
    || S-NSSAI=0x01:0x00            ||
    || EP_Transport:                ||
    || - ipAddress = UPF-CN1-if     ||
    || - connectionPointIDType =    ||
    ||        "ATTACHMENT_CIRCUIT"  ||
    || - connectionPointId = "ac1"--------+
    |+------------------------------+|    |
    +--------------------------------+    |
                                          V
                  +------------------------------------------------+
                  | * "ac1" properties:                            |
                  |     - vlan-id: 100                             |
                  |     - src-port = 5678                          |
                  |     - CE address (gNB-CU): gNB-AN2-if          |
                  |     - PE address: 192.0.2.2/30                 |
                  |     - Routing: static 198.51.100.0/24 via      |
                  |                192.9.2.1 tag primary_UP_slice  |
                  +------------------------------------------------+
```

Figure 3: Slice Mapping using UDP source port

Figure 3 shows the configuration and mapping applied to network instances in a 3GPP network slice subnet and corresponding TN instances for sending an upstream GTP packet from gNB-CU (user plane) to UPF. The gNB-CU (user plane) function is in a data center (site 1) and separated from the IP transport slice provider by an AC ("ac1" in Figure 3). The AC ("ac1") is for an EP_Transport configured as specified in [TS.28.541-3GPP] and realized using [RFC9834] and related extensions for GTP (UDP tunnel) in [I-D.jlu-dmm-udp-tunnel-acaas].

In this example, a GTP-U packet at gNB-CU (user plane) is from a UE session with S-NSSAI = 0x01:0x00 and to be forwarded to UPF-CN1 (i.e., as already setup by SMF during PDU session establishment). The associated 3GPP and TN instances in the figure provide mapping to slice resources. The gNB-CU (UP) uses the slice mapping to "ac1" shown in Figure 3 when forwarding the GTP-U packet to UPF-CN1-if with source address of gNB-AN2-if and UDP source port number 5678 (GTP-U /UDP outer encapsulation source port). The slice mapping proposed in this document does not depend on VLANs, however, this example is to illustrate that the UDP mapping can be used in conjunction with other AC properties. The GTP-U packet is forwarded by the data center network to the PE router at IP backhaul network. The PE matches on VLAN ID of GTP-U packet and IP source port to select the provisioned slice (NS = TS2). The GTP-U packet is then forwarded to the UPF. For a downstream GTP-U packet, the UPF customer edge may similarly be attached to a PE and have similar slice configuration and mapping (details are not shown in the figure).

PEs can thus be provisioned with a policy based on the source UDP port number (and other identifiers like VLAN) to the underlying transport path and then deliver the QoS/slice resource provisioned in the TN. The source UDP port number that is encoded is the outer IP (corresponding to GTP-U header) while the inner IP packet (UE payload) is unaltered. The source UDP port number is encoded by the node that creates the GTP-U encapsulation and therefore, this mechanism has no impact on UDP checksum calculations.

3GPP network operators may use IPsec gateways (SEG) to secure packets between two sites - for example over an F1-U, N3 or N9 segment. The IP network slice identifier in the GTP-U packet should be in the outer IP source port number even after IPSec encryption for PE transport routers to inspect and provide the level of service provisioned. Tunnel mode - which is the case for SEG/IPSec gateways - adds an outer IP header in both AH (Authenticated Header) and ESP (Encapsulated Security Payload) modes. The IPSec secured GTP-U packet should be UDP encapsulated and the GTP-U source port number copied to the outer UDP encapsulation source port number for the PE to select the slice. When GTP-U packets use the source port number as an entropy field for load balancing, copying it to the outer UDP source port number would preserve this as intended for load balancing [RFC8085], section 5.1.1. UDP source port and ranges in Figure 4 allow for slice selection at the PE when the UDP source port is also used for load balancing.

4. Transport Network Underlays

Traffic engineered underlay networks are an essential component to realize the slicing defined in this document. TNs should be able to realize midhaul, backhaul and control plane slices shown in Figure 1. This section outlines how GTP/UDP source ports are used to map to slice types. [RFC9543], section 7 describes in more detail how a network slice can be realized over different TN technologies including enhanced VPN, IP/MPLS and SR-TE.

An example with different user plane slice types and transport paths is shown in the figure. In this case with 3 different 3GPP Slice and Service Types (SSTs), 3 transport TE paths are setup. For uplink traffic, an underlying TE transport path may be from a gNB-CU to a UPF for example. A similar downlink path and underlying transport from UPF to gNB-CU is configured. The figure shows UDP port ranges, SST, transport path (in this example pseudowire/VPN) and transport path characteristics.

GTP/UDP SRC PORT	SST in S-NSSAI	Transport Path Info	Transport Path Characteristics
Range Xx - Xy X1, X2(discrete values)	MIoT (massive IoT)	PW ID/VPN info, TE-PATH-A	GBR (Guaranteed Bit Rate) Bandwidth: Bx Delay: Dx Jitter: Jx
Range Yx - Yy Y1, Y2(discrete values)	URLLC (ultra-low latency)	PW ID/VPN info, TE-PATH-B	GBR with Delay Req. Bandwidth: Bx Delay: Dx Jitter: Jx
Range Zx - Zy Z1, Z2(discrete values)	EMBB (broadband)	PW ID/VPN info, TE-PATH-C	Non-GBR Bandwidth: Bx

Figure 4: Mapping of Transport Paths on F1-U/N3/N9

In some E2E scenarios, additional path characteristics with finer granularity may be desired in the underlying TN, such as for security. In such cases, there would be a need to have separate sub-ranges under each SST to provide the TE path in preserving the security characteristics. The UDP source port range captured in Figure 4 would be sub-divided to maintain the TE path for the current SSTs with the security. The current solution doesn't provide any mandate on the UE traffic in selecting the type of security.

There are many possible TN technologies that may be used to realize these slices. These are described in [RFC9543].

5. Acknowledgements

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6. Security Considerations

This document specifies the use of UDP source port to identify a (customer) 3GPP slice at the TN provider edge (PE). The YANG model should conform to security constraints described in [I-D.jlu-dmm-udp-tunnel-acaas] and [RFC9834].

Section 3 describes the configuration and management of slices that may be deployed with 3GPP nodes or PE nodes that are not in the trusted operator boundary. To avoid spoofing and other attacks, security mechanisms with ACLs and IPSec must be deployed. The configuration and management procedures here should conform to security constraints for slice authentication, isolation, data confidentiality and integrity, and privacy described in section 10 of [RFC9543].

7. IANA Considerations

This document has no requests for IANA code point allocations.

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Appendix A. Abbreviations

5G-AN â\200\223 5G Access Network

5GS â\200\223   5G System

AC â\200\223   Attachment Circuit

CSR â\200\223   Cell Site Router

CP â\200\223   Control Plane (5G)

CU â\200\223   Centralized Unit (5G, gNB)

DN â\200\223   Data Network (5G)

DU â\200\223   Distributed Unit (5G, gNB)

eMBB â\200\223   enhanced Mobile Broadband (5G)

gNB â\200\223   Next Generation Node B

GBR â\200\223   Guaranteed Bit Rate (5G)

GTP-U â\200\223 GPRS Tunneling Protocol - User plane (3GPP)

MIoT â\200\223   Massive IoT (5G)

MPLS â\200\223   Multi Protocol Label Switching

NG-RAN â\200\223 Next Generation Radio Access Network (i.e., gNB, NG-eNB - RAN functions which connect to 5GC)

NSC â\200\223   Network Slice Controller

NSS â\200\223   Network Slice Subnet

NSSAI â\200\223 Network Slice Selection Assistance Information

NSSI â\200\223   Network Slice Subnet Identifier

NSSF â\200\223   Network Slice Selection Function

PDU â\200\223   Protocol Data Unit (5G)

PW â\200\223   Pseudo Wire

SDP â\200\223   Service Demarcation Point

S-NSSAI â\200\223 Single Network Slice Selection Assistance Information

SD â\200\223   Slice Differentiator (5G)

SST â\200\223   Slice and Service Types (5G)

SR â\200\223   Segment Routing

TE â\200\223   Traffic Engineering

UP â\200\223   User Plane(5G)

UPF â\200\223   User Plane Function (5G)

URLLC â\200\223 Ultra reliable and low latency communications (5G)

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Problems and Requirements of Satellite Constellation for Internet
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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

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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.

To integrate the satellite network with Internet, many other technologies are needed to provide the functions on different layeres. Currently, there are four major international SDO (standard organizations) involved in the development of different technologies: IETF, 3GPP, CCSDS (Consultative Committee for Space Data Systems [CCSDS]), DVB (Digital Video Broadcast [DVB]). Section 4.1 will discuss the different protocol stacks based on different combinations of technologies from different SDOs.

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 4.2), another is for the integration with 3GPP wireless network including 4G and 5G (see Section 4.3 and Section 4.4).

It must be noted that we use 3GPP as an use case example does not mean other technologies cannot be used, e.g., using DVB instead of 3GPP for the satellite network integration. We use 3GPP is because 3GPP has done the most thorough research and produced lots of solutions for satellite networking, such as using 5G NR for satellite up link and down link, use transparent pay load and regenerative pay load for different scenarios, etc. (see Section 4.3).

4.1. Protocol Stack for Satellite Networking with Different Technologies

Figure 1 illustrates three typical protocol statcks that use different technology combinations. This does not include the use of private technologies for wireless and Link Layer such as Starlink.

The stacks show obviously that TCP/IP is the common technologies, IETF has to (at least) provide the L3 and L4 technologies for satellite networking integrated with Internet.

```
  +-------------------+ +--------------------+ +-------------------+
  |5G upper layers(SA)| | CCSDS upper layers | |  DVB upper layers |
  +-------------------+ +--------------------+ +-------------------+
  |      TCP/UDP      | |      TCP/UDP       | |      TCP/UDP      |
  |         IP        | |         IP         | |         IP        |
  +-------------------+ +--------------------+ +-------------------+
  |       SDAP        | |        IPoC        | |       IPoGSE      |
  |       PDCP        | |                    | |                   |
  |        RLC        | |        USLP        | |    DVB MPE/GSE    |
  |        MAC        | |                    | |                   |
  +-------------------+ +--------------------+ +-------------------+
  |      3GPP RF;     | |     CCSDS RF;      | |   DVB S2/S2X/T2;  |
  | 3GPP Spectrum;FSO | | CCSDS Spectrum;FSO | | DVB Spectrum; FSO |
  +-------------------+ +--------------------+ +-------------------+
       3GPP Stacks           CCSDS Statks            DVB Stacks
```

Figure 1: Protocol Statcks for Different Standard Technologies

Some meaning of symbols in Figure 1 are as follows:

SA Service Architecture

SDAP SService Data Adaption Protocol

PDCP	Packet Data Convergence Protocol
RLC	Radio Link Control
MAC	Medium Access Control
RF	Radio Frequency
FSO	Free Space Optics, provided by ITU
IPoC	IP over CCSDS
USLP	Unified Space Link Protocol
IPoGSE	IP over Generic Stream Encapsulation
MPE	Multiprotocol Encapsulation
GSE	Generic Stream Encapsulation
S2	Digital Video Broadcasting Satellite Second Generation
S2X	Digital Video Broadcasting Satellite Second Generation Extension
T2	Digital Video Broadcasting Satellite Second Generation Terrestrial

4.2. 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 2 for one satellite relay, Figure 3 for multiple satellite relay).

2. The end user terminal access Internet through inter-satellite-networking (Figure 4).

3. The local network access Internet through satellite relay
    (Figure 5 for one satellite relay, Figure 6 for multiple
    satellite relay).

4. The local network access Internet through inter-satellite-
networking
    (Figure 7).

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

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

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

Figure 3: 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 4: End user terminal access Internet through inter-
satellite-networking

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

Figure 5: Local network access Internet through one satellite relay

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

Figure 6: 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 7: Local network access Internet through inter-satellite-networking

In above Figure 2 to Figure 7, 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

The above configuration may have different variations, e.g., the GW and GS functions can be merged into one ohysical devices.

4.3. 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 8 for mobile access network to satellite network, and Figure 9 for satellite network to mobile access network.

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

Figure 8: 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 9: End user terminal or local network access Internet through Satellite Network and Mobile Access Network

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

3GPP SA Working Groups (WG) feature a couple of satellite-related projects (or SIDs).

For Release 18, 3GPP has finished the project 'Study on 5G System with Satellite Backhaul' [TR-23.700-27] and 'Study on 5GC enhancement for satellite access Phase 2' [TR-23.700-28].

For Release 19, 3GPP will study more topics for satellite network used for 5G system, such as Regenerative payload generic architecture study, Store and Forward Satellite operation, etc.

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 10 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 10: 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 2 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 11) 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 11: 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

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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 12 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 13 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 12: Satellite coverage on ground

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

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

Figure 13: 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 12.

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 14 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 14: 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 14, 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 15 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 16 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 15: 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 16: 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 17 illustrates a general case that two satellites move and intersect with an angle A.

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

Figure 17: Two satellites (speed vector V1 and V2) intersect with angle A

More specifically, for orbit planes with the inclination angle i, Figure 18 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 18: 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 19 illustrates two satellites (with the altitude difference Da) move and intersect with an angle A.

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

Figure 19: 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
* 05 version, 7/5/2023
* 06 version, 1/3/2024

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Semantic Address Based Instructive Routing for Satellite Network
draft-lhan-satellite-instructive-routing-03

Abstract

This document presents a method to do IP routing over satellite network that consists of LEO (Low Earth Orbit) satellites and ground-stations. The method uses the source routing mechanism. The whole routing info is obtained by path calculation. The routing path information is converted to be a list of instructions and embedded into user packet's IPv6 extension header. At each hop or each satellite, the routing process engine will forward the packet based on the specified instruction for the satellite. Until the packet reaches the edge of satellite network, or the last satellite, the packet will be sent to a ground station.

Status of This Memo

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1. Introduction

Massive LEO constellation is expected to be used for future Internet. It has raised challenges to the current IP networking technologies to support such super-fast-moving network. [I-D.lhan-problems-requirements-satellite-net] has analyzed the problems when using the regular routing protocols in such network.

Since all satellites in a LEO constellation are well organized and form a kind of multi-layered grid network, each satellite's relative position in the satellite network will be steady during its life time. [I-D.lhan-satellite-semantic-addressing] has proposed to use couple of indexes to identify each satellite in the network. The combination of the indexes is called the satellite semantic address. The semantic address can be embedded into the field of the interface identifier (i.e., the rightmost 64 bits) of the IPv6 address, if IPv6 is used in the satellite network.

This memo proposes a method for routing for LEO satellite network, it is based on the satellite semantic address. It is a source routing mechanism and conceptually similar to SRv6 (IPv6 Segment Routing) [RFC8754] with loose-hop, but with many differences in the architecture and details. The routing information is embedded into the IPv6 packet as routing extension header defined in [RFC8200]. Unlike the SRv6 [RFC8754] and programming [RFC8986], The new method will not use IPv6 SID (Segment Identifier) to represent the segments on the routing path. Instead, it will convert the segments on the path to be a list of instructions since each satellite could be represented by the semantic address. Each instruction can tell each satellite how to forward the packet to an adjacent satellite and when to stop, either on the same orbit, or on the adjacent orbit.

Compared with the traditional IP forwarding, the new method will not use TCAM (Ternary Content-addressable Memory) lookup for IP prefix. Each satellite only needs to store a simple adjacency table. Therefore, the new method can save significant TCAM and the processing time for routing/forwarding tables.

It must be noted this memo just describes one aspect of the whole solution for satellite constellation used for Internet access and NTN (Non-Terrestrial Network) integration with 5G, following areas are not covered in this memo and will be addressed in other documents separately:

1. IP forwarding path determination for a LEO constellation. There are different strategies and algorithms to determine the IP path. One example using modified OSPF and Dijkstra algorithm [I-D.retana-lsr-ospf-monitor-node] to get the shortest geographic path can be found in [Large-Scale-LEO-Network-Routing].

2. Data planes for different scenarios, such as Internet access and NTN integration.

3. Other protocols for control plane.

2. Terminology

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

LEO constellation — LEO constellation consists of certain number of LEOs. Each LEO has pre-assigned orbit element.

ISL — Inter Satellite Link

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

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

OS — Operating System

NTN — Non-Terrestrial Network

SID — Segment Identifier

Sat-GS Links — Wireless links between satellites and ground-stations, it consists of uplink (from ground to satellite) and downlink (from satellite to ground.

Link Metrics — The cost of the outgoing interface for routing, typically, it may indicate the bandwidth, delay or other costs for the interface.

Sat_ID
: Satellite Index, the Index for the satellite in a orbit plane, see [I-D.lhan-satellite-semantic-addressing]

Obp_ID
: Orbit Plane Index, the Index for the orbit plane in a shell group of satellite, see [I-D.lhan-satellite-semantic-addressing]

Shl_ID
: Shell Index, the Index for the shell group of satellite in a satellite constellation, see [I-D.lhan-satellite-semantic-addressing]

Intf_ID
: Interface Index

Sat_Addr
: Satellite Semantic Address, it consists of indexes Shl_ID, Obp_ID and Sat_ID. It is 32-bit long and is defined in Section 5.4 in [I-D.lhan-satellite-semantic-addressing]

Sat_MacAddr
: The MAC (Media Access Control) Address for a satellite

3. Review of LEO satellite constellation for future Internet

LEO satellite constellation is expected to be integrated with terrestrial network in future Internet. StarLink project [StarLink] has launched its satellites and provided the beta service in some areas. 3GPP [ThreeGPP] has studied the issues when NTN is integrated with Internet and 5G. 3GPP [TR38-821] has also proposed the Satellite-based NG-RAN architectures for NTN integration. In the 3GPP new Release 18 (in-progress), there is a working item "Study on 5G System with Satellite Backhaul" [TR23-700]. In which, LEO satellite network will provide the transport functionality for 5G RAN access network. As a summary, the targets of LEO constellation for future Internet and NTN integration are as follows:

1. Global coverage: The Satellite network should cover all places on earth and any flying objects as long as the place or objects are below LEO attitude and within the coverage footprint of satellite constellation, the satellite network should be the complementary to terrestrial network.

2. Internet access: The Satellite network can provide the Internet access service for covered areas.

3. NTN integration: The Satellite network is fully integrated with Internet including Wireless such as 4G or 5G.

4. Competitive service: The Satellite network can provide the services that are competitive to terrestrial network in terms of service stability, Quality of Service, especially the latency for Satellite network is shorter.

As a new form of network, LEO constellation has lots of difference with the steady terrestrial network especially in the mobility. [I-D.lhan-problems-requirements-satellite-net] has analyzed the movement and coverage of satellite. For a massive LEO constellation, all satellites are moving on the allocated orbits, and form one or multiple layers of network. Finally, the massive LEO constellation will have the following unprecedented mobility:

1. Each LEO moves at the speed of 7.x km/s.

2. Ground Stations move at the speed of 463 m/s due to earth rotation.

3. Half of LEOs move on the direction that is different with another half of LEOs.

4. Huge number of links between satellites and ground-stations, and all of them are constantly flipping within short period of time. All Link Metrics of Sat-GS Links are also constantly changing.

5. All Link Metrics of ISL on the Longitude direction are constantly changing.

6. All Links of ISL on the Longitude direction may be interrupted at two polar areas.

7. All Link Metrics of ISL on the radius direction (for satellites with different altitude) are constantly changing.

8. All Links of ISL on the radius direction can only last for a limited time.

4. Basics of Instructive Routing

In IP routing or forwarding, the IP path consists of a list of IP nodes (hops). In LEO satellite network, the IP forwarding path is a list of satellites. Instructive routing essentially is a mechanism that converts satellites on the path to a list of segment and then to a list of instructions. It will utilize the special characters of LEO satellite network to achieve the minimized packet overhead while the forwarding functions can be executed quickly.

A typical LEO satellite network is an interleaved and meshed network moving constantly. Each satellite only has limited adjacent satellites, thus the limited packet forwarding directions (see Section 4.1).

The satellites on a forwarding path can be converted to a list of segments. The number of segments is normally much smaller than the number of satellites on the path.

The number of segment type will determine the number of instruction type. Since the segment type is also limited (see Section 4.2), so the instruction type is limited.

Finally, combining the above characters and with the use of semantic address, the Instructive Routing will only introduce limited overhead that is much smaller than SRv6 and SRv6 with compressed SID.

4.1. Forwarding Directions

When using ISL for satellites in a LEO constellation, each layer of network will have satellite nodes connected by limited ISLs. A typical satellite will have about six ISL to connected to its adjacent satellites in 3D space. Additionally, there might have very few numbers of ISL working as un-steady link to connect to other satellites. Un-stead links are those between satellites moving to different directions, see [I-D.lhan-problems-requirements-satellite-net] for the detailed explanation. After using the semantic address for each satellite, the satellite relationship will be static. Figure 1 illustrates one satellite and its six direct connected adjacent satellites, it is easy to determine some indexes of its adjacent satellites:

1. S0, S1 and S2 have the same Shl_ID, the difference of Obp_ID between S0 and S1, S0 and S2 are both equal to one.

2. S0, S3 and S4 have the same Shl_ID and Obp_ID, the difference of Sat_ID between S0 and S3, S0 and S4 are both equal to one.

3. S0, S5 and S6 have different Shl_ID, and the difference of Shl_ID between S0 and S5, S0 and S6 are both equal to one.

Another benefit to use the semantic address is that the packet forwarding for routing and switching will be simplified significantly. There will be only six major forwarding directions to the directly connected adjacent satellites described above, plus one or few specified directions probably. The specified direction is to forward packet to a specified adjacent satellite through an un-steady link. The un-steady link can connect to any satellite but only last for a short time. The usages of un-steady links are expected to be limited and are not major scenarios in a LEO constellation. Following are all directions for forwarding:

1. Forward to the Sat_ID Incremental or Decremental directions.

2. Forward to the Obp_ID Incremental or Decremental directions.

3. Forward to the Shl_ID Incremental or Decremental directions.

4. Forward to a specified satellite through an un-steady link.

```
                       ^ Shl_ID Incremental direction
                       |
                         /
                        /
                       S5    ^ Sat_ID Increment direction
                      /|    /
                     / |   S3
                  / /  |  /       /
                 / /   | /       /
                /      |/       /
               S2------S0------S1  -> Obp_ID Increment direction
              /       /|   /  /
             /       / | /  /
            /       /  | /  /
                   S4  |/
                       S6
                      /
                     /
                    /
```

Figure 1: The LEO Satellite Relationship in 3D Space

4.2. Forwarding Segments

A forwarding segment is defined as a list of satellites, and four type segments are defined for LEO satellite network where semantic address is used:

1. Segment with adjacent Shl_ID: For any direct adjacent satellites on the segment, their Shl_ID are also adjacent (differ by one).

2. Segment with adjacent Obp_ID: For any direct adjacent satellites on the segment, their Obp_ID are also adjacent (differ by one), the Shl_ID are the same.

3. Segment with adjacent Sat_ID: For any direct adjacent satellites on the segment, their Sat_ID are also adjacent (differ by one), the Obp_ID and Shl_ID are identical.

4. Segment with non-adjacent index: this segment only has two satellites and two satellites do not belong to the above three categories.

4.3. Forwarding Instructions

Each forwarding instruction consists of Functional Code and Argument (see Section 6). For the most often used instructions, the Argument represents one specified index (Sat_ID or Obp_ID or Shl_ID) of a satellite semantic address and only has the size of one octet.

Each segment maps to a forwarding instruction that can guides the packet forwarded at each satellite from the start to the end of the segment. For the segment types (1) to (3) described in Section 4.2, there are two directions to forward packet, each direction can be defined as either an increment or a decrement of a specified index. For type (4), there is one direction to forward packet. In total we have seven directions to forward packets among all satellites: to the satellite ahead or behind; to either sides; above or below; or to another non-adjacent satellite.

When an IP packet is forwarded on a segment by an instruction, at each satellite, the forwarding logic needs to check if the packet reaches the end of the segment. In the regular segment routing, the long size of SID is used to do such indication. But for satellite network, since 32-bit satellite's semantic address is embedded into the IPv6 address, it is not needed to include the long SID into the packet header. Instead, we only need to compare one octet index of the current satellite's semantic address, instead of whole IPv6 address, with the Argument in the instruction.

4.4. Example

Figure 2 illustrates a 2D example. It shows how a packet is forwarded in a grid satellite network. Intuitively, we can obtain the list of instructions to guide the packet and get the forwarding behaviors at different satellites. Following is an example:

1. At S1 to S2, forward packet to the Sat_ID Incremental direction, until the packet reaches S2

2. At S2 to S3, forward packet to the Obp_ID Incremental direction, until the packet reaches the orbit plane of S3

3. At S3 to S4, forward packet to the Sat_ID Incremental direction, until the packet reaches S4

4. At S4 to S5, forward packet to the Obp_ID Decremental direction, until the packet reaches the orbit plane of S5

5. At S5 to S6, forward packet to the Sat_ID Decremental direction, until the packet reaches S6

By using a specified index of semantic address as the argument as described in Section 4.3, we can further simplify the above instructions as:

1. At S1 to S2, forward packet to the Sat_ID Incremental direction, until the packet reaches a satellite and the satellite's Sad_ID is equal to the given instruction argument (S2's Satellite Index)

2. At S2 to S3, forward packet to the Obp_ID Incremental direction, until the packet reaches a satellite and the satellite's Obp_ID is equal to the given instruction argument (S3's Orbit Plane Index)

3. At S3 to S4, forward packet to the Sat_ID Incremental direction, until the packet reaches a satellite and the satellite's Sat_ID is equal to the given instruction argument (S4's Satellite Index)

4. At S4 to S5, forward packet to the Obp_ID Decremental direction, until the packet reaches a satellite and the satellite's Obp_ID is equal to the given instruction argument (S5's Orbit Plane Index)

5. At S5 to S6, forward packet to the Sat_ID Decremental direction, until the packet reaches a satellite and the satellite's Sat_ID is equal to the given instruction argument (S6's Satellite Index)

```
               ^ Sat_ID Incremental Direction
               |
               |
               +----> Obp_ID Incremental Direction

               x: The ISL is down

                    Obp_ID Obp_ID+1 Obp_ID+2 Obp_ID+3 Obp_ID+4
                       |       |       |       |       |
                   ----+-------S5<<<<<<S<<<<<<<S4------+----
                       |       V       x       ^       |
                       |       V       |       ^       |
                   ----+-------S6------+---x---S-------+----
                       |       |       |       ^       |
                       x       x       x       ^       |
                   ----S2>>>>>>S>>>>>>>S>>>>>>>S3------+----
                       ^       |       |       |       |
                       ^       |       |       |       |
                   ----S---x---+-------+-------+-------+----
                       ^       |       |       |       |
                       ^       |       |       |       |
                   ----S1--x---+-------+-------+-------+----
                       |       |       |       |       |
                       |       |       |       |       |
```

Figure 2: Packet Forwarding in 2D LEO satellite constellation network

5. IPv6 Routing Header for Instructive Routing

For instructive routing, IPv6 routing header is used with a new routing type "Instructive Routing Type". The format of the new routing header is illustrated in Figure 3.

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    | Next Header   |  Hdr Ext Len  | Routing Type  | Inst. Offset  |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |Remained Inst. | ST  |               Rsvd                      |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                            Inst. List                         ~
    |                                               +-+-+-+-+-+-+-+-+
    |                                               ~   paddings    |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: The IPv6 Routing Hdr for Instructive Routing

Routing Type   Instructive Routing Type

Inst. Offset   The offset in the number of octets from the start of Instruction List. The initial value is set to 0 and it points to the 1st instruction to be executed. The value is incremented by the number of octets of the total size of an instruction after the instruction is executed.

Remained Inst. Remained Number of Instructions. The initial value is set to the total number of instructions. The value will be decremented by one after one instruction is executed. The minimum number is one, and it indicates that the end of instruction stack is reached.

ST   The satellite address type, default is 0.

Inst. List   A list of instructions, the size is variable.

Paddings   Pad1 or PadN options to make the packet extension header alignment, see [RFC8200]

6. Instruction List for Instructive Routing

For instructive routing, the instruction list is used to instruct each satellite how to do routing job. The format of the instruction list is illustrated in Figure 4. Each instruction consists of Function Code and Arguments.

```
    0                   1                   2                   3
   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |  Func. Code   |    Arguments  | Func. Code    |  Arguments    ~
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  \--------------\/--------------/ \--------------\/--------------/
           instruction[0]                   instruction[1]...
```

Figure 4: The Instruction List for Instructive Routing

Func. Code   Function Code, size is 1 octet

Arguments   Arguments for the function, Variable length

7. Instructive Routing Behaviors

The behavior for each satellite for instructive routing is described here. Table 1 is the summary of the name, Hex values of all functions, arguments and size. New functions can be defined if needed.

The subsections below are the detailed explanation for each function.

Func Name/Hex Value	Arguments/Size(Octet)	Reference
Fwd.Inc.Sat_ID/0X01	Sat_ID/1	Section 7.1
Fwd.Dec.Sat_ID/0X02	Sat_ID/1	Section 7.2
Fwd.Inc.Obp_ID/0X03	Obp_ID/1	Section 7.3
Fwd.Dec.Obp_ID/0X04	Obp_ID/1	Section 7.4
Fwd.Inc.Shl_ID/0X05	Shl_ID/1	Section 7.5
Fwd.Dec.Shl_ID/0X06	Shl_ID/1	Section 7.6
End.Intf_ID/0X07	Intf_ID/1	Section 7.7
End.Punt/0X08	0X0/1	Section 7.8
End.Lookup/0X09	0X0/1	Section 7.9
End.Lookup.IPv4/0X0A	IPv4_Addr/4	Section 7.10
End.Lookup.IPv6/0X0B	IPv6_Addr/16	Section 7.11
Fwd.Sat_Addr/0X0C	Sat_Addr/4	Section 7.12
Fwd.Sat_MacAddr/0X0D	Sat_MacAddr/6	Section 7.13

Table 1: Functions, Arguments and Reference

The functions in Section 7.1 to Section 7.6 are used for the instructions to forward packet to one of the six major directions discussed in Section 4. They will call API in Section 7.14 to forward the packet to the specified direction.

The functions in Section 7.12 and Section 7.13 are used for the instructions to forward packet to a specified adjacent satellite discussed in Section 4. They will call APIs in Section 7.15 and Section 7.16 respectively to forward the packet to the specified adjacent satellite.

In order to forward packet, each satellite should have an adjacency table stored locally; the table should contain the information about all adjacent satellites, it should at least store:

1. Each adjacent satellite's semantic address.

2. The ID of local interface connecting to each adjacent satellite.

3. The MAC address for the remote interface of each adjacent satellite.

7.1. Fwd.Inc.Sat_ID

The definition of this function is "Forward the packet on the Satellite Index Incremental Direction until the packet reaches a Satellite whose Satellite Index is equal to the value specified in the argument"

This function is used for the instruction to forward packet to one of the six major directions discussed in Section 4.

When a satellite receives a packet with new routing header, assume the satellite indexes in the address are Shl_index, Obp_index, Sat_index respectively, the satellite does the following. During the forwarding, the Forwarding_API in Section 7.14 is called to forward the packet to the specified direction.

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Sat_index)) {
S03.      Input_Satellite = Current Satellite;
S04.      Input_Direction = Satellite Index Incremental direction;
S05.      Forwarding_API(Packet,Input_Satellite,Input_Direction);
S06.   } else {
S07.      IOF += 2;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet;
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.2. Fwd.Dec.Sat_ID

The definition of this function is "Forward the packet on the Satellite Index Decremental Direction until the packet reaches a Satellite whose Satellite Index is equal to the value specified in the argument"

This function is used for the instruction to forward packet to one of the six major directions discussed in Section 4.

When a satellite receives a packet with new routing header, assume the satellite indexes in the address are Shl_index, Obp_index, Sat_index respectively, the satellite does the following. During the forwarding, the Forwarding_API in Section 7.14 is called to forward the packet to the specified direction.

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Sat_index)) {
S03.      Input_Satellite = Current Satellite;
S04.      Input_Direction = Satellite Index Decremental direction;
S05.      Forwarding_API(Packet,Input_Satellite,Input_Direction);
S06.   } else {
S07.      IOF += 2;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet;
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.3. Fwd.Inc.Opb_ID

The definition of this function is "Forward the packet on the Orbit Plane Index Incremental Direction until the packet reaches a Satellite whose Orbit Plane Index is equal to the value specified in the argument"

This function is used for the instruction to forward packet to one of the six major directions discussed in Section 4.

When a satellite receives a packet with new routing header, assume the satellite indexes in the address are Shl_index, Obp_index, Sat_index respectively, the satellite does the following. During the forwarding, the Forwarding_API in Section 7.14 is called to forward the packet to the specified direction.

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Obp_index)) {
S03.      Input_Satellite = Current Satellite;
S04.      Input_Direction = Orbit Plane Index Incremental direction;
S05.      Forwarding_API(Packet,Input_Satellite,Input_Direction);
S06.   } else {
S07.      IOF += 2;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet;
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.4. Fwd.Dec.Opb_ID

The definition of this function is "Forward the packet on the Orbit Plane Index Decremental Direction until the packet reaches a Satellite whose Orbit Plane Index is equal to the value specified in the argument"

This function is used for the instruction to forward packet to one of the six major directions discussed in Section 4.

When a satellite receives a packet with new routing header, assume the satellite indexes in the address are Shl_index, Obp_index, Sat_index respectively, the satellite does the following. During the forwarding, the Forwarding_API in Section 7.14 is called to forward the packet to the specified direction.

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Obp_index)) {
S03.      Input_Satellite = Current Satellite;
S04.      Input_Direction = Orbit Plane Index Decremental direction;
S05.      Forwarding_API(Packet,Input_Satellite,Input_Direction);
S06.   } else {
S07.      IOF += 2;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet;
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.5. Fwd.Inc.Shl_ID

The definition of this function is "Forward the packet on the Orbit Shell Index Incremental Direction until the packet reaches a Satellite whose Orbit Shell Index is equal to the value specified in the argument"

This function is used for the instruction to forward packet to one of the six major directions discussed in Section 4.

When a satellite receives a packet with new routing header, assume the satellite indexes in the address are Shl_index, Obp_index, Sat_index respectively, the satellite does the following. During the forwarding, the Forwarding_API in Section 7.14 is called to forward the packet to the specified direction.

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Shl_index)) {
S03.      Input_Satellite = Current Satellite;
S04.      Input_Direction = Orbit Shell Index Incremental direction;
S05.      Forwarding_API(Packet,Input_Satellite,Input_Direction);
S06.   } else {
S07.      IOF += 2;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet;
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.6. Fwd.Dec.Shl_ID

The definition of this function is "Forward the packet on the Orbit Shell Index Decremental Direction until the packet reaches a Satellite whose Orbit Shell Index is equal to the value specified in the argument"

This function is used for the instruction to forward packet to one of the six major directions discussed in Section 4.

When a satellite receives a packet with new routing header, assume the satellite indexes in the address are Shl_index, Obp_index, Sat_index respectively, the satellite does the following. During the forwarding, the Forwarding_API in Section 7.14 is called to forward the packet to the specified direction.

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Shl_index)) {
S03.      Input_Satellite = Current Satellite;
S04.      Input_Direction = Orbit Shell Index Decremental direction;
S05.      Forwarding_API(Packet,Input_Satellite,Input_Direction);
S06.   } else {
S07.      IOF += 2;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet;
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.7. End.Intf_ID

The definition of this function is "End of processing for the Instructive routing, remove the Instructive Routing Header, Forward the packet to the interface specified in the argument"

This function is normally used on the Dst_Sat to forward packet to Dst_GS.

When a satellite receives a packet with new routing header, the satellite does the following, Forwarding_GS_API in Section 7.17 is called to forward the packet to the specified interface.

```
S01. When an IRH is processed {
S02.   Change the Next header in the packet header to be
          the Next Header field in the Instructive Routing header;
S03.   Remove the Instructive Routing Header;
S04.   Forwarding_GS_API(Packet, Argument);
S05.}
```

7.8. End.Punt

The definition of this function is "End of processing for the Instructive routing, remove the Instructive Routing Header, Punt the packet to the OS for process"

This function is normally used send packet to a satellite. At the destination satellite, the packet is punted to the OS to be processed further.

When a satellite receives a packet with new routing header, the satellite does the following:

```
S01. When an IRH is processed {
S02.   Change the Next header in the packet header to be
         the Next Header field in the Instructive Routing header;
S03.   Remove the Instructive Routing Header;
S04.   Punt packet to the local CPU for process;
S05.}
```

7.9. End.Lookup

The definition of this function is "End of processing for the Instructive routing, remove the Instructive Routing Header, Lookup the destination address in packet header and forward the packet accordingly"

This function is normally used to send packet to Dst_GS. After the packet reaches the Dst_Sat, the packet is forwarded to Dst_GS by looking up the destination address in the IPv6 packet header.

When a satellite receives a packet with new routing header, the satellite does the following:

```
S01. When an IRH is processed {
S02.   Change the Next header in the packet header to be
         the Next Header field in the Instructive Routing header;
S03.   Remove the Instructive Routing Header;
S04.   Lookup the destination address in packet hdr and forward
         the packet;
S05.}
```

7.10. End.Lookup.IPv4

The definition of this function is "End of processing for the Instructive routing, remove the Instructive Routing Header, Lookup the IPv4 address specified in the argument and forward the packet accordingly"

This function is normally used to send packet to Dst_GS. After the packet reaches the Dst_Sat, the packet is forwarded to Dst_GS by looking up the IPv4 destination address specified in the Function Argument.

When a satellite receives a packet with new routing header, the satellite does the following:

```
S01. When an IRH is processed {
S02.   Fetch the IPv4 addr in the argument;
S03.   Change the Next header in the packet header to be
         the Next Header field in the Instructive Routing header;
S04.   Remove the Instructive Routing Header;
S05.   Lookup the fetched IPv4 address and forward the packet;
S06.}
```

7.11. End.Lookup.IPv6

The definition of this function is "End of processing for the Instructive routing, remove the Instructive Routing Header, Lookup the IPv6 address specified in the argument and forward the packet accordingly"

This function is normally used to send packet to Dst_GS. After the packet reaches the Dst_Sat, the packet is forwarded to Dst_GS by looking up the IPv6 destination address specified in the Function Argument.

When a satellite receives a packet with new routing header, the satellite does the following:

```
S01. When an IRH is processed {
S02.   Fetch the IPv6 addr in the argument;
S03.   Change the Next header in the packet header to be
         the Next Header field in the Instructive Routing header;
S04.   Remove the Instructive Routing Header;
S05.   Lookup the fetched IPv6 address and forward the packet;
S06.}
```

7.12. Fwd.Sat_Addr

The definition of this function is "Forward the packet to the adjacent satellite with the address specified in the argument"

This function is normally used for the instruction to forward packet to an adjacent satellite specified by its Satellite Semantic Address. The Satellite Semantic Address is 32-bit long and is defined in Section 5.4 in [I-D.lhan-satellite-semantic-addressing]

When a satellite receives a packet with new routing header, assume the satellite semantic address is Sat_Addr, the satellite does the following:

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Sat_Addr)) {
S03.      Input_Satellite = Current Satellite;
S04.      SatAddr = Argument;
S05.      Forwarding_API_SAT(Packet,Input_Satellite,SatAddr);
S06.   } else {
S07.      IOF += 4;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet.
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.13. Fwd.Sat_MacAddr

The definition of this function is "Forward the packet to the adjacent satellite with the MAC address specified as the argument"

This function is normally used for the instruction to forward packet to an adjacent satellite specified by its MAC address.

When a satellite receives a packet with new routing header, assume the satellite Mac address is Sat_MacAddr, the satellite does the following:

```
S01. When an IRH is processed {
S02.   If ((RI > 1) and (Argument != Sat_MacAddr)) {
S03.      Input_Satellite = Current Satellite;
S04.      SatMacAddr = Argument;
S05.      Forwarding_API_Mac(Packet,Input_Satellite,SatMacAddr);
S06.   } else {
S07.      IOF += 6;
S08.      RI --;
S09.      if (RI <= 0)
              Send an ICMP Parameter Problem to the Source Address
              with Code 0 (Erroneous header field encountered)
              and Pointer set to the RI field,
              interrupt packet processing, and discard the packet.
S10.      Proceed to execute the next Instruction;
S11.   }
S12.}
```

7.14. Forwarding_API(Packet,Input_Satellite,Input_Direction)

This API will forward a packet to the specified direction. When a satellite executes the API, it will do following:

```
S01. Forwarding_API(Packet,Input_Satellite,Input_Direction) {
S02.    Lookup the local adjacency table to find out
           1) The adjacent satellite of "Input_Satellite" on the
              direction equal to "Input_Direction" (The adjacent
              satellite's semantic address can be inferred by
              the "Input_Satellite" and "Input_Direction").
           2) The L2 address for the adjacent satellite;
           3) The local interface connecting to the adjacent
              satellite;
S03.    Rewrite the L2 header of the Packet by the L2 address;
S04.    Send the Packet to the local interface;
S05.}
```

7.15. Forwarding_API_SAT(Packet,Input_Satellite,Sat_Addr)

This API will forward a packet to the specified adjacent satellite with the semantic address as the argument. When a satellite executes the API, it will do following:

```
S01. Forwarding_API_SAT(Packet,Input_Satellite,SatAddr) {
S02.    Lookup the local adjacency table to find out
           1) The adjacent satellite of "Input_Satellite"
              (The adjacent satellite address is SatAddr);
           2) The L2 address for the adjacent satellite;
           3) The local interface connecting to the adjacent
              satellite;
S03.    Rewrite the L2 header of the Packet by the L2 address;
S04.    Send the Packet to the local interface;
S05.}
```

7.16. Forwarding_API_MAC(Packet,Input_Satellite,Sat_MacAddr)

This API will forward a packet to the specified adjacent satellite with the MAC address as the argument. When a satellite executes the API, it will do following:

```
S01. Forwarding_API_MAC(Packet,Input_Satellite,SatMacAddr) {
S02.    Lookup the local adjacency table to find out
           1) The adjacent satellite of "Input_Satellite"
              (The adjacent satellite MAC address is SatMacAddr);
           2) The L2 address for the adjacent satellite;
           3) The local interface connecting to the adjacent
              satellite;
S03.    Rewrite the L2 header of the Packet by the L2 address;
S04.    Send the Packet to the local interface;
S05.}
```

7.17. Forwarding_GS_API(Packet,Input_Interface)

This API will forward a packet to ground station the connected to the specified interface. When a satellite executes the API, it will do following:

```
S01. Forwarding_API(Packet,Input_Interface) {
S02.    Lookup the local adjacency table to find out
           1) The connected GS to the interface
              equal to "Input_Interface";
           2) The L2 address for the GS;
S03.    Rewrite the L2 header of the Packet by the L2 address;
S04.    Send the Packet to the "Input_Interface";
S05.}
```

8. Other notes

Due to the limit of the picture drawing for IETF draft, the pictures in the memo may not be easy to understand. For easier understanding of the method, please refere to the [Large-Scale-LEO-Network-Routing], it provided more vivid pictures obtained by simulation software Savi [Savi], and also provided the simulation results.

9. IANA Considerations

This document defines a new IPv6 Routing Type: the "Instructive Routing Header". It needs to be assigned a number by IANA.

This document also defines an 8-bit Function Name, for which IANA will create and will maintain a new sub-registry entitled "Instructive Routing Function Name" under the "Internet Protocol Version 6 (IPv6) Parameters" [IPv6_Parameters] registry. Initial values for the subtype registries are given in Table 1.

10. Security Considerations

The instructive routing is only applicable to a satellite network that is using the satellite semantic address. It will add instructive routing header at a GS and the header will be removed before reaching another GS. Normally, a satellite network including all GS is trusted domain. Traffic will be filtered at the domain boundaries. Non-authorized users cannot access the satellite network.

11. Contributors

12. Acknowledgements

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Appendix A. Change Log

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* Revision 2, 03/03/2023

* Revision 3, 09/01/2023

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Satellite Semantic Addressing for Satellite Constellation
draft-lhan-satellite-semantic-addressing-04

Abstract

This document presents a semantic addressing method for satellites in satellite constellation connecting with Internet. The satellite semantic address can indicate the relative position of satellites in a constellation. The address can be used with traditional IP address or MAC address or used independently for IP routing and switching.

Status of This Memo

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1. Introduction

Satellite constellation technologies for Internet are emerging and expected to provide Internet service like the traditional wired network on the ground. A typical satellite constellation will have couple of thousands or over ten thousand of LEO and/or VLEO. Satellites in a constellation will be connected to adjacent satellites by Inter-Satellite-Links (ISL), and/or connected to ground station by microwave or laser links. ISL is still in research stage and will be deployed soon. This memo is for the satellite networking with the use of ISL.

The memo proposes to use some indexes to represent a satellite's orbit information. The indexes can form satellite semantic address, the address can then be embedded into IPv6 address or MAC address for IP routing and switching. The address can also be used independently if the shorter than 128-bit length of IP address is accepted. As an internal address for satellite network, it only applies to satellites that will form a constellation to transport Internet traffic between ground stations and will not be populated to Internet by BGP.

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

GEO Geosynchronous orbit with the altitude 35786 km

ISL Inter Satellite Link

ISLL Inter Satellite Laser Link

3D Three Dimensional

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.

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]

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

For IP based satellite networking, the topology is very dynamic and the traditional IGP and BGP based routing technologies will face challenges according to the analysis in [I-D.lhan-problems-requirements-satellite-net]. From the paper, we can easily categorize satellite links as two types, steady and un-steady. For un-steady links, the link status will be flipping every couple of minutes.

Section 5.5 has more details about how to identify different links.

Some researches have been done to handle such fast changed topologies. one method to overcome the difficulties for routing with un-steady links is to only use the steady links, and get rid of un-steady links unless it is necessary. For example, for real deployment, only links between satellite and ground stations are mandatory to use, other un-steady links can be avoided in routing and switching algorithms. [Routing-for-LEO] proposed to calculate the shortest path by avoiding un-steady links in polar area and links crossing Seam line since satellites will move in the opposite direction crossing the Seam line.

Traditionally, to establish an IP network for satellites, each satellite and its interface between satellites and to ground stations have to be assigned IP addresses (IPv4 or IPv6). The IP address can be either private or public. IP address itself does not mean anything except routing prefix and interface identifier [RFC8200].

To utilize the satellite relative position for routing, it is desired that there is an easy way to identify the relative positions of different satellites and identify un-steady links quickly. The traditional IP address cannot provide such functionality unless we have the real-time processing for 3D coordinates of satellites to figure out the relative positions of each satellite, and some math calculation and dynamic database are also needed in routing algorithm to check if a link is steady or not. This will introduce extra data exchanged for routing protocols and burden for the computation in every satellite. Considering the ISL link speed (up to 10G for 2000km) and hardware cost (Radiation-hardened semiconductor components are needed) in satellite are more constraint than for network device on ground, it is expected to simplify the routing algorithm, reduce the requirement of ISL, onboard CPU and memory.

The document proposes to form a semantic address by satellite orbit information, and then embedded it into a proper IP address. The IP address of IGP neighbors can directly tell the relative position of different satellites and if links between two satellites are stead or not.

The document does not describe the details how the semantic address is used to improve routing and switching or new routing protocols, those will be addressed in different documents. Instructive routing [I-D.lhan-satellite-instructive-routing] is a new proposal to use the semantic address for the routing of large-scale LEO satellite network. It is based on source routing mechnism and meshing characteristics of LEO satellite constellation, using semantic address can reduce the overheader of the instruction for the packet forwarding at each satellite. The complete solution combining the semantic address, the instructive routing and modified OSPF [I-D.retana-lsr-ospf-monitor-node] can be found in [Large-Scale-LEO-Network-Routing].

4. Basics of Satellite Constellation and Satellite Orbit

This section will introduce some basics for satellite such as orbit parameters.

4.1. 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)

The circular orbit is widely used by proposals of satellite constellation from different companies and countries.

For a circular orbit, we will have:

* Eccentricity e = 0

* Semimajor axis a = Altitude of satellite

* Argument of periapsis omega = 90 degree

So, three parameters, Altitude, Inclination and Longitude of the ascending node, will be enough to describe the orbit. The satellite will move in a constant speed and True anomaly (nu) can be easily calculated after the epoch time is defined.

4.2. Satellite Constellation Compositions

One satellite constellation may be composed of many satellites (LEO and VLEO), but normally all satellites are grouped in a certain order that is never changed during the life of satellite constellation. Each satellite constellation's orbits parameters described in Section 4.1 must be approved by regulator and cannot be changed either. Follows are characters of one satellite constellation:

1. One Satellite Constellation is composed of couple of shell groups of satellites.

2. The same shell group of satellites will have the same altitude and inclination angle.

3. The total No orbit planes in the same shell group of satellites will be evenly distributed by the same interval of Longitude of the ascending node (Omega). The interval equals to (360 degree/ No). As a result, all orbit planes in the same shell group will effectively form a shell to cover earth (there will be a coverage hole for the shell on the sky in both polar areas if the inclination angle is less than 90 degree).

4. Each orbit plane in the same shell group will have the same number of satellites, all satellites in the same orbit plane will be evenly distributed angularly in the orbit plane. Assuming there are Ns satellites in each orbit plane, then the angular interval of satellites equals to (360 degree/Ns).

5. All satellites in the same shell group are moving in the same circular direction. As a result, at any location on earth, we can see there will have two group of satellites moving on the opposite direction. One group moves from south to north, and another group moves from north to south. Section 5.5 has more details.

4.3. Communication between Satellites by ISL

When ISL is used for the communication between satellites, each satellite will have a fixed number of links to connect to its neighbor. Due to the cost of ISL and the constraints of power supply on satellite, the number of ISL is normally limited to connect to its closest neighbors. In 3D space, each satellite may have six types of adjacent satellites, each type represents one direction. The number of adjacent neighbors in one direction is dependent on the number of deployment of ISL device on satellites, for example, the laser transmitter and receiver for ISLL. Figure 1 illustrates satellite S0 and its adjacent neighbors.

```
                 /           /           /
                /           /           /
               /           /           /
              S7          S8          S9
             /           /           /
            /           /           /
           /           /           /
                 /           S1          /
                S5          /           S3
               /           /           /
              /           S0          /
             /           /           /
            S6          /           S4
           /           S2          /
                 /           /           /
                /           /           /
               /           /           /
              S10         S11         S12
             /           /           /         ^ Moving direction
            /           /           /         /
           /           /           /         /
          orbit      orbit       orbit
```

Figure 1: Satellite S0 and its adjacent neighbors

All adjacent satellites of S0 in Figure 1 are listed below:

1. The front adjacent satellite S1 that is on the same orbit plane as S0.

2. The back adjacent satellite S2 that is on the same orbit plane as S0

3. The right adjacent satellites S3 and S4 that are on the right orbit plane of S0

4. The left adjacent satellites S5 and S6 that are on the left orbit plane of S0

5. The above adjacent satellites S7 to S9 that are on the above orbit plane of S0

6. The below adjacent satellite S10 to S12 that are on the below orbit of plane S0

The relative position of adjacent satellites will directly determine the quality of ISL and communication. From the analysis in [I-D.lhan-problems-requirements-satellite-net], The speed of satellite is only related to the altitude of the satellite (on circular orbit), all satellites with a same altitude will move with the same speed. So, in above adjacent satellites, some adjacent satellite’s relative positions are steady and the ISL can be alive without interruption caused by movement. Some adjacent satellites relative positions are changing quickly, the ISL may be down since the distance may become out of reach for the laser of ISL, or the quick changed positions of two satellite make the tracking of laser too hard. Below are details:

* The relative position of satellites in the same orbit plane will be the steadiest.

* The relative position of satellites in the direct neighbor orbit planes in the same shell group and moving in the same direction will be steady at equator area, but will be changing when two orbits meet on the polar area. Whether the link status will be flipping depends on the tracking technology and the range of laser pointing angle of ISL. See Figure 2.

* The relative position of satellites in the neighbor orbit planes in the same shell group but moving in the different direction will not be steady at all times. More details are explained in Figure 8

* The relative position of satellites in the neighbor orbit planes in the different shell group will be dependent on the difference of altitude and inclination. This has been analyzed in [I-D.lhan-problems-requirements-satellite-net].

```
                  \      /
                   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
    * So, if the range of laser pointing angle is 360 degree and
      tracking technology supports, the ISL will not be flipping
      after passing polar area; Otherwise, the link will be flipping
```

Figure 2: Satellite's Position and ISL Change at Polar Area

5. Addressing of Satellite

When ISL is deployed in satellite constellation, all satellites in the constellation can form a network like the wired network on ground. Due to the big number of satellites in a constellation, the network could be either L2 or L3. The document proposes to use L3 network for better scalability.

When satellites form a L3 network, it is expected that IP address is needed for each satellite and its ISLs.

While the traditional IP address can still be used for satellite network, the document proposes an alternative new method for satellite's addressing system. The new addressing system can indicate a satellite's orbit info such as shell group index, orbit plane index and satellite index. This will make the adjacent satellite identification for link status easier and benefit the routing algorithms.

5.1. Indexes of Satellite

As described in Section 4.2, one satellite has three important orbit related information as described below.

1. Index for the shell group of satellites in a satellite constellation

2. Index for the orbit plane in a shell group of satellites

3. Index for the satellite in an orbit plane

It should be noted that for all type of indexes, it is up to the owner to assign the index number. There is no rule for which one should be assigned with which number. The only important rule is that all index number should be in sequential to reflect its relative order and position with others. Below is an example of assignment rules:

1. The 1st satellite launched in an orbit plane can be assigned for the 1st satellite index (0), the incremental direction of the satellite index in the same orbit plane is the incremental direction of "Argument of periapsis (omega)"

2. The 1st orbit plane established can be assigned for the 1st orbit plane index (0), the incremental direction of the orbit plane index is the incremental direction of "Longitude of the ascending node (Omega)".

3. The shell group of satellites with the lowest altitude can be assigned for the 1st shell group index (0), the incremental direction of shell group index is the incremental direction of altitude.

It should also be noted that for all type of indexes assignment, there are no strict requirement for the physical positions of satellite. Due to the launching time difference, the shifing of the satellite orbit after some time, the orbit parameters of satellites always have some difference and do not follow the theoritical values. For example:

1. The altitude of all satellites in the same shell group might not be exactly same.

2. The inclination angle of all satellites in the same shell group might not be exactly same.

3. The Longitude of the ascending node (Omega) of all satellites in the same orbit plane might not be exactly same.

4. The interval of the Longitude of the ascending node (Omega) of all orbit plane in the same shell group might not be equal

5. The angular interval of all satellites in the same orbit plane might not be equal.

Figure 3 and Figure 4 illustrate three types of indexes for satellite

```
             /           /           /   \
            /           /           /    |
           /           /           /     |
          S           S           S      > shell group3
         /           /           /       |
        /           /           /        |
       /           /           /         /
             /           S           /   \
            S           /           S    |
           /           /           /     |
          /           S           /       > shell group2
         /           /           /       |
        S           /           S        |
       /           S           /         /
             /           /           /   \
            /           /           /    |
           /           /           /     |
          S           S           S       > shell group1
         /           /           /       |
        /           /           /        |
       /           /           /         /
      orbit     orbit      orbit           ----> Earth self-rotation
      plane1    plane2     plane3
```

Figure 3: Shell Group and Orbit Plane Indexes for Satellites

Shell Group and Orbit Plane Indexes for Satellites

```
                   , - ~ S1 ~ - ,
               S2 '              ' S8
             ,                      ,
            ,                        ,
           ,                          ,      Indexed
           S3                         S7 <-- satellite
           ,                          ,      in one orbit plane
            ,                        ,
             ,                      ,      ^  move direction
               S4                 , S6     /
                 ' - , _ S5_ ,  '         /
```

Figure 4

Three types of Index for satellites

5.2. The Range of Satellite Indexes

The ranges of different satellite indexes will determine the range the dedicated field for semantic address. The maximum indexes depend on the number of shell group, orbit plane and satellite per orbit plane. The number of orbit plane and satellite per orbit plane have relationship with the coverage of a satellite constellation. There are minimum numbers required to cover earth. [I-D.lhan-problems-requirements-satellite-net] has given the detailed math to estimate the minimal number required to cover the earth. There are two key parameters that determine the minimal number of satellite required. One is the elevation angle, another is the altitude. StarLink has proposed two elevation angles, 25 and 35 degrees [SpaceX-Non-GEO]. The lowest LEO altitude can be 160km according to [Lowest-LEO-ESA]. The Table 1 and Table 2 illustrate the estimation for different altitude (As), the coverage radius (Rc), the minimal required number of orbit planes (No) and satellite per orbit plane (Ns). The elevation angle is 25 degree and 35 degrees respectively.

Parameters	VLEO1	VLEO2	LEO1	LEO2	LEO3	LEO4	LEO5
As(km)	160	300	600	900	1200	1500	2000
Rc(km)	318	562	1009	1382	1702	1981	2379
Ns	73	42	23	17	14	12	10
No	85	48	27	20	16	14	12

Table 1: Satellite coverage (Rc), minimal number of orbit plane (No) and satellite (Ns) per orbit plane for different LEO/VLEOs, Elevation angle = 25 degree

Parameters	VLEO1	VLEO2	LEO1	LEO2	LEO3	LEO4	LEO5
As(km)	160	300	600	900	1200	1500	2000
Rc(km)	218	392	726	1015	1271	1498	1828
Ns	107	59	32	23	19	16	13
No	123	69	37	27	22	18	15

Table 2: Satellite coverage (Rc), minimal number of orbit plane (No) and satellite (Ns) per orbit for different LEO/VLEOs, Elevation angle = 35 degree

The real deployment may be different as above analysis. Normally, more satellites and orbit planes are used to provide better coverage. So far, there are only two proposals available, one is StarLink, another is from China Constellation. For proposals of [StarLink], there are 7 shell groups, the number of orbit plane and satellites per orbit plane in all shell groups are 72 and 58; For proposals of [China-constellation], there are 7 shell groups, the number of orbit plane and satellites per orbit plane in all shell groups are 60 and 60;

It should be noted that some technical parameters, such as the inclination and altitude of orbit planes, in above proposals may be changed during the long-time deployment period, but the total numbers for indexes normally do not change.

From the above analysis, to be conservative, it is safe to conclude that the range of all three satellite indexes are less than 256, or 8-bit number.

5.3. Other Info for satellite addressing

In addition to three satellite indexes described in Section 5.1, other information is also important and can also be embedded into satellite address:

1. The company or country code, or the owner code. In the future, there may have multiple satellite constellations on the sky from different organizations, and the inter-constellation communication may become as normal that is similar to the network on the ground. This code will be useful to distinguish different satellite constellation and make the inter-constellation communication possible. One satellite constellation will have one code assigned by international regulator (IANA or ITU). Considering the following facts:

    * The space of LEO satellite orbits is limited. New LEO satellite orbits need ITU’s approve.

    * The spectrum for LEO satellite communication is limited. New spectrum needs ITU’s approve.

    * The costs of satellite constellations in launching, maintenance and operation are considerably high.

    We can predict the total number of satellite constellation is very limited. So, the size of code is limited. In the draft, we propose to use one octet for Owner code.

2. The Interface Index. This index is to identify the ISL or ISLL for a satellite. As described in Section 4.3, the total number of ISL is limited. So, the size of interface index is also limited.

5.4. Encoding of Satellite Semantic Address

The encoding for satellite semantic address is dependent on what routing and switching (L2 or L3 solution) technologies are used for satellite networking, and finally dependent on the decision of IETF community.

Follows are some initial proposals:

1. 32-bit satellite semantic address (Figure 5) can be used for Router ID if IGP, i.e, OSPF, is used for the routing within the satellite network. Note, this does not hint the current OSPF can be used for satellite network without any changes. Separate drafts should be written to describe the details about the modified OSPF for satellite network routing.

2. When satellite network is using L3 or IPv6 solution, the satellite semantic address is encoded as the interface identifier (i.e., the rightmost 64 bits) of the IPv6 address for IPv6. Figure 6 shows the format of IPv6 Satellite Address.

3. When satellite network is using L2 solution, the satellite semantic address can be embedded into the field of "Network Interface Controller (NIC) Specific" in MAC address [IEEE-MAC-Address]. But due to shorter space for NIC, the "Index for the shell group" and "Index for Interface" will only have 4-bit. This is illustrated in Figure 7. This encoded MAC address can also be used for L3 solution where the interface MAC may be also needed to be configured for each ISL.

4. Recently, some works suggested to use Length Variable IP address for routing and switching [Length-Variable-IP] or use flexible IP address [I-D.jia-flex-ip-address-structure] or shorter IP address [I-D.li-native-short-addresses] to solve some specific problems that regular IPv6 is not very suitable. Satellite network also belongs to such specific network. Due to the resource and cost constraints and requirement for radiation hardened electronic components, the ISL speed, on-board processor and memory are limited in performance, power consumption and capacity compared with network devices on ground. So, using IPv6 directly in satellite network is not an optimal solution because IPv6 header size is too long for such small network. From above analysis, 32-bit to 64-bit length of IP address is enough for satellite networking. Using 128-bit IPv6 will consume more resource especially the ISL bandwidth, processing power and memory, etc. If shorter than 128-bit IP address is accepted as IETF work, the satellite semantic address can be categorized as a similar use case. Figure 5 illustrates a 32-bit Semantic Satellite Address format. The final coding for the shorter IP address can be decided by the community. How to use the 32-bit Semantic Satellite address can be addressed later on in different document.

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |   Owner Code  |  Shell_Index  |  Orbit_Index  |   Sat_Index   |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Owner Code: Identifier for the owner of the constellation
Shell_Index: Index for the shell group of satellite in a satellite
             constellation
Orbit_Index: Index for the orbit plane in a shell group of satellite
Sat_Index: Index for the satellite in an orbit plane

Figure 5: The 32-bit Semantic Satellite Address

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    ~                     Subnet Prefix (64 bits)                   ~
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |   Owner Code  |  Shell_Index  |  Orbit_Index  |   Sat_Index   |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |   Intf_Index  |                    Reserved                   |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Owner Code: Identifier for the owner of the constellation
Shell_Index: Index for the shell group of satellite in a satellite
             constellation
Orbit_Index: Index for the orbit plane in a shell group of satellite
Sat_Index: Index for the satellite in an orbit plane
Intf_Index: Index for interface on a satellite
Reserved: 24-bits reserved

Figure 6: The IPv6 Satellite Address

```
              3 Octets             3 Octets
        /---------^--------\ /--------^--------\
        +-------------------+-------------------+
        |        OUI        |    Sat Address    |
        +-------------------+-------------------+
                                     |
                                     |
     +-------------------------------+
     |
     |
     v

      0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    | Shell |  Orbit_Index  |    Sat_Index   |Intf_Id|
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

    OUI: Organizationally Unique Identifier assigned by IEEE
    Shell: 4-bit Index for the shell group of satellite in a satellite
           constellation
    Orbit_Index: Index for the orbit plane in the group of satellite
    Sat_Index: Index for the satellite in the orbit plane
    Intf_Id: 4-bit Index for interface on a satellite
```

Figure 7: The MAC Satellite Address

5.5. Link Identification by Satellite Semantic Address

Using above satellite semantic addressing scheme, to identify steady and un-steady links is as simple as below:

Assuming:

1. The total number of satellites per orbit plane is M

2. The total number of orbit planes per shell group is N.

3. Two satellites have:

    * Satellite Indexes as: Sat1_Index, Sat2_Index

    * Orbit plane Indexes as: Orbit1_Index, Orbit2_Index

    * Shell group Indexes as: Shell1_Index, Shell2_Index

Steady links:

1. The links between adjacent satellites on the same orbit plane, or, the satellite indexes satisfy:

   * Sat2_Index = Sat1_Index + 1, when Sat1_Index < M-1; Sat2_Index = 0, when Sat1_Index = M-1; and

   * Orbit1_Index = Orbit2_Index, Shell1_Index = Shell2_Index.

2. The links between satellites on adjacent orbit planes on the same altitude. and two satellites are moving to the same direction, or, the satellite indexes satisfy:

   * Orbit2_Index = Orbit1_Index + 1, when Orbit1_Index < N-1; Orbit2_Index = 0, when Orbit1_Index = N-1; and

   * Shell1_Index = Shell2_Index.

   * Sat1_Index and Sat2_Index may be equal or have difference, depend on how the link is established.

Un-Steady links:

1. The links between satellite and ground stations.

2. The links between satellites on adjacent orbit planes on the same altitude. Two satellites are moving to the different direction. Or, the satellite indexes do not satisfy conditions described in above #2 for Steady links.

3. The links between satellites on adjacent orbit planes on different altitude. Or, the satellite indexes satisfy:

   * Shell1_Index != Shell2_Index.

Figure 8 illustrates the links for adjacent orbit planes (#2 for Steady Link and Un-steady Link above). From the figure, it can be noticed that some links may have shorter distance than steady link, but they are unsteady. For example, the links between S1 and S4; S4 and S2; S2 and S5, etc.

```
                   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.
* Dot lines are the steady links

Figure 8: The links between satellites on adjacent orbit planes

6. Other notes

Due to the limit of the picture drawing for IETF draft, the pictures in the memo may not be easy to understand. For easier understanding of the method, please refere to the [Large-Scale-LEO-Network-Routing], it provided more vivid pictures obtained by simulation software Savi [Savi].

7. IANA Considerations

This memo may include request to IANA for owner code, see Section 5.4.

8. Security Considerations

The semantic address for satellite only describes the relative positions of satellites, it does not introduce more security issues compared with the normal IP address. Similar to terrestrial network, a satellite network normally will have different protocols at the different layers, form L1 to L7, to provide the security for a satellite network.

9. Contributors

10. Acknowledgements

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Appendix A. Change Log

* Initial version, 10/19/2021

* 01 version, 02/28/2022

* 02 version, 09/02/2022

* 03 version, 03/03/2023

* 04 version, 09/01/2023

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23 October 2023

Mobile User Plane Architecture using Segment Routing for Distributed Mobility Management

draft-mhkk-dmm-srv6mup-architecture-06

Abstract

This document defines the Mobile User Plane (MUP) architecture using Segment Routing (SR) for Distributed Mobility Management. The requirements for Distributed Mobility Management described in [RFC7333] can be satisfied by routing fashion.

Mobile services are deployed over several parts of IP networks. An SR network can accommodate a part of those networks, or all those networks. IPv6 dataplane option (SRv6) is suitable for both cases especially for the latter case thanks to the large address space, so this document illustrates the MUP deployment cases with IPv6 dataplane.

MUP Architecture can incorporate existing session based mobile networks. By leveraging Segment Routing, mobile user plane can be integrated into the dataplane. In that routing paradigm, session information between the entities of the mobile user plane is turned to routing information.

Status of This Memo

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1. Introduction

Mobile services require IP connectivity for communication between the entities of mobile service architecture [RFC5213][TS.23501]. To provide the IP connectivity, Segment Routing (SR) [RFC8402]can be a candidate solution.

In PMIPv6 [RFC5213], IP connectivity between LMA and MAG can be provided over SR networks, as well as LMA and Internet. In 3GPP 5G [TS.23501], IP connectivity for N3 interface between gNodeB(es) and UPFs can also be provided by SR, as well as for N6 interface between UPFs and DNs (Data Network).

These IP connectivities may be covered by multiple SR networks, or just one SR network, depending on the size of the deployment. In the latter case, it is expected that the address space of the SR network should be large enough to cover a vast number of nodes, such as millions of base stations. For this reason, use of IPv6 for the SR dataplane looks sufficiently suitable.

SRv6 is an instantiation of SR over IPv6 dataplane in which a single network can accommodate all entities of mobile services thanks to the huge available address space and network programming capability described in [RFC8986].

Meanwhile, SRv6 network programmability enhances SRv6 dataplane to be integrated with mobile user plane [I-D.ietf-dmm-srv6-mobile-uplane]. It will make an entire SRv6 network support the user plane in a very efficient distributed routing fashion.

On the other hand, the requirements for Distributed Mobility Management (DMM) described in [RFC7333] can be satisfied by session management based solutions. [RFC8885] defines protocol extension to PMIPv6 for the DMM requirements. 3GPP 5G defines an architecture in which multiple session anchors can be added to one mobility session by the session management.

As a reminder, the user plane related requirements in [RFC7333] are reproduced here:

REQ1: Distributed mobility management

IP mobility, network access solutions, and forwarding solutions provided by DMM MUST enable traffic to avoid traversing a single mobility anchor far from the optimal route. It is noted that the requirement on distribution applies to the data plane only.

REQ3: IPv6 deployment

DMM solutions SHOULD target IPv6 as the primary deployment environment and SHOULD NOT be tailored specifically to support IPv4, particularly in situations where private IPv4 addresses and/or NATs are used.

REQ4: Existing mobility protocols

A DMM solution MUST first consider reusing and extending IETF standard protocols before specifying new protocols.

REQ5: Coexistence with deployed networks/hosts and operability across different networks

A DMM solution may require loose, tight, or no integration into existing mobility protocols and host IP stacks. Regardless of the integration level, DMM implementations MUST be able to coexist with existing network deployments, end hosts, and routers that may or may not implement existing mobility protocols. Furthermore, a DMM solution SHOULD work across different networks, possibly operated as separate administrative domains, when the needed mobility management signaling, forwarding, and network access are allowed by the trust relationship between them.

This document defines the Mobile User Plane (MUP) architecture using Segment Routing for Distributed Mobility Management. MUP is not a mobility management system itself, but an architecture enables the SR dataplanes to integrate mobile user plane into it for the IP networks.

In this routing paradigm, session information from a mobility management system will be transformed to routing information. It means that mobile user plane specific nodes for the anchor or intermediate points are no longer required. The user plane anchor and intermediate functions can be supported by SR throughout an SR domain (REQ1), not to mention that MUP will naturally be deployed over IPv6 networks (REQ3).

MUP architecture is independent from the mobility management system. For the requirements (REQ4, 5), MUP architecture is designed to be pluggable user plane part of existing mobile service architectures. Those existing architectures are for example defined in [RFC5213], [TS.23501], or if any.

The level of MUP integration for mobile networks running based on the existing architecture will be varied and depending on the level of SR awareness of the control and user plane entities.

Specifying how to modify the existing architecture to integrate MUP is out of scope of this document. What this document provides for the existing architecture is an interface for MUP which the existing or future architectures can easily integrate.

1.1. Requirements Language

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].

2. Terminology

MUP: Mobile User Plane

MUP Segment: Representation of mobile user plane segment

MUP PE: MUP aware Provider Edge node

MUP Controller: Controller node for an SR network

UE: User Equipment, as per [TS.23501]

MN: Mobile Node, as per [RFC5213]

3. Architecture Overview

In the MUP architecture, a network segment consists of a mobile service is represented as a MUP segment. This document introduces new segment types of MUP segment called "Direct segment", and "Interwork Segment". Other segment types may be specified in another document in the future. A MUP PE may accommodate MUP segment(s), such as an Interwork Segment and/or a Direct Segment. Figure 1 depicts the overview.

```
                             *   Mobility   *
                              * Management *
                               *  System  *
                                *........*
                                     |
                            Session Information
                                     |
                       ______________v______________
        _______       /           |MUP-C|           \       _______
       /       \     /            +-----+            \     /       \
      /Interwork\__  |                               |  __/ Direct  \
      \ Segment /  \ |-------+               +------| /  \ Segment /
       \_______/    \| MUP PE|       SR      |MUP PE|/    \_______/
        _______     /|-------+     Network   +------|\     _______
       /       \   / |                               | \   /       \
      / Direct  \_/   \                             /   \_/Interwork\
      \ Segment /      \___________________________/      \ Segment /
       \_______/                                           \_______/
```

Figure 1: Overview of MUP Architecture

This document also defines new routing information called "Segment Discovery route" and "Session Transformed route". A MUP PE sends and/or receives these types of routing information, and does the dataplane action indicated by the routing information at wherever the MUP PE instantiated. The illustrations are described in Section 7.

To carry these new routing information, this architecture requires extending the existing routing protocols. Any routing protocol can be used to carry this information but this document recommends using BGP. Thus, this document describes extensions on BGP as an example.

4. Mobile User Plane Segment

This document defines two new types of Mobile User Plane (MUP) segment. A MUP segment represents a network segment consisting of a mobile service. The MUP segment can be created by a MUP PE which provides connectivity for the mobile user plane.

Direct Segment is a type of MUP segment that provides connectivity between MUP segments through the SR network. Interwork Segment is another type of MUP segment. It provides connectivity between a user plane protocol of existing or future mobile service architecture and other MUP segments through the SR networks.

A MUP PE may be instantiated as a physical node or a virtual node. The MUP PE may also be instantiated on a device which accomodates a mobile user plane node of a mobility management system.

4.1. IPv6 Dataplane

An SRv6 SID (Segment Identifier) can represent a MUP segment. The SID can be any behavior defined in [RFC8986], [I-D.ietf-dmm-srv6-mobile-uplane], or any other extensions for further use cases. The behavior of the MUP segment will be chosen by the role of the representing MUP segment.

For example, in case of a MUP PE interfaces to 5G user plane on the access side defined as "N3" in [TS.23501], the MUP PE accommodates the N3 network as Interwork Segment in a routing instance and then the behavior of created segment SID by the MUP PE will be "End.M.GTP4.E", or "End.M.GTP6.E". In this case, the MUP PE may associate the SID to the routing instance for the N3 access network (N3RAN).

Another example here is that a MUP PE interfaces to 5G DN on the core side defined as "N6" in [TS.23501], the MUP PE accommodates the N6 network in a routing instance as Direct Segment and then the behavior of the created segment SID by the MUP PE will be "End.DT4", "End.DT6", or "End.DT2". In this case, the MUP PE may associate the SID to the routing instance for the N6 data network (N6DN).

5. Distribution of Mobile User Plane Segment Information

Distribution of MUP segment information can be done by advertising routing information with the MUP segment for mobile service. A MUP PE distributes MUP segment information when a MUP segment is connected to the MUP PE.

A MUP Segment Discovery route is routing information that associates the MUP segment with network reachability. This document defines the basic discovery route types, Direct Segment Discovery route, and Interwork Segment Discovery route. Other types of segment discovery route may be mobile service architecture specific. Defining the architecture specific network reachability is out of scope of this document and it will be specified in another document.

5.1. Direct Segment Discovery Route

When a MUP PE accommodates a network through an interface or a routing instance as a Direct Segment, the MUP PE advertises the corresponding Direct Segment Discovery route for the interface or the routing instance to the SR domain. The Direct Segment Discovery route includes an address of the MUP PE in the network reachability information with an extended community indicating the corresponding Direct Segment, and the SID for the segment.

For example in 3GPP 5G specific case, an MUP PE may connect to N6 interface on a DN side, an MUP Segment Discovery route for the DN will be advertised with an address of the MUP PE, corresponding SID and Direct Segment extended community to the routing instance for the DN from the MUP PE.

When a MUP PE receives a Direct Segment Discovery route from other PEs, the MUP PE keeps the received Direct Segment Discovery route in the RIB. The MUP PE uses the received Direct Segment Discovery route to resolve Type 2 session transformed routes reachability, described in Section 6.2. If the Direct Segment Discovery route resolves reachability for the endpoints, and match the Direct Segment extended community of the Type 2 session transformed routes, the MUP PE updates the FIB entry for the Type 2 session transformed route with the SID of the matched Direct Segment Discovery route.

5.2. Interwork Segment Discovery Route

When a PE accommodates a network through an interface or a routing instance for the user plane protocol of the mobile service architecture as an Interwork Segment, the PE advertises the corresponding Interwork Segment Discovery route with the prefixes of the Interwork Segment and the corresponding SID of the prefixes to the SR domain.

For example in 3GPP 5G specific case, an Interwork Segment Discovery route for N3 network accommodating RAN will be incorporated in an N3RAN segment discovery route associated with a RAN segment SID.

When a MUP PE receives a Interwork Segment Discovery route, the MUP PE keeps the received Interwork Segment Discovery routes in the RIB. The MUP PE uses the received Interwork Segment Discovery routes to resolve the reachability for remote endpoint of Type 1 session transformed routes, described in Section 6.1. If the Interwork Segment Discovery route resolves the reachability for Type 1 session transformed routes, the MUP PE updates the FIB entry for the prefix of Type 1 session transformed route with the SID of the matched MUP segment discovery route.

The received Interwork Segment Discovery routes MUST be used to resolve reachability for the remote endpoints of Type 1 session transformed routes. The connectivity among the routing instances for Interwork Segments may be advertised as VPN routes. This is to avoid forwarding entries to the prefixes of Interwork Segment mingled in the other type of routing instance. A MUP PE may discard the received Interwork segment discovery route if the Route Target extended communities of the route does not meet the MUP PE’s import policy.

6. Distribution of Session Transformed Route

MUP architecture defines two types of session transformed route.

6.1. Type 1 Session Transformed Route

First type route, called Type 1 Session Transformed route, encodes IP prefix(es) for a UE or MN in a BGP MP-NLRI attribute with associated session information of the tunnel endpoint identifier on the access side. The MUP controller advertises the Type 1 Session Transformed route with the Route Target extended communities for the UE or MN to the SR domain.

A MUP PE may receive the Type 1 Session Transformed routes from the MUP Controller in the SR domain. The MUP PE may keep the received Type 1 Session Transformed routes advertised from the MUP Controller. The receiving MUP PE will perform the importing of the received Type 1 Session Transformed routes in the configured routing instances based on the Route Target extended communities. A MUP PE may discard the received Type 1 Session Transformed route if the MUP PE fails to import the route based on the Route Target extended communities.

6.2. Type 2 Session Transformed Route

Second type route, called Type 2 Session Transformed route, encodes the tunnel endpoint identifier of the session on the core side in a BGP MP-NLRI attribute with the nature of tunnel decapsulation. Longest match algorithm for the prefix in this type of session transformed route should be applicable to aggregate the routes for scale. The MUP controller advertises the Type 2 Session Transformed route with the Route Target and Direct Segment extended communities for the endpoint to the SR domain.

A MUP PE may receive the Type 2 Session Transformed routes from the MUP Controller in the SR domain. The MUP PE may keep the received Type 2 Session Transformed routes advertised from the MUP Controller. The receiving MUP PE will perform the importing of the received Type 2 Session Transformed routes in the configured routing instances based on the Route Target extended communities. A MUP PE may discard the received Type 2 Session Transformed route if the MUP PE fails to import the route based on the Route Target extended communities.

6.3. MUP Controller

A MUP controller provides an API. A consumer of the API inputs session information for a UE or a MN from mobility management system. The MUP controller transforms the received session information to routing information and will advertise the session transformed routes with the corresponding extended communities to the SR domain.

The received session information is expected to include the UE or MN IP prefix(es), tunnel endpoint identifiers for both ends, and any other attributes for the mobile networks. For example in a 3GPP 5G specific case, the tunnel endpoint identifier will be a pair of the F-TEIDs on both the N3 access side (RAN) and core side (UPF).

7. Illustration

This section illustrates possible MUP deployments with IPv6 dataplane. 3GPP 5G is an example mobile service for the deployment cases in this section.

7.1. SR Network Accommodating Existing Mobile Network Services

Figure 2 shows how SR networks can accommodate existing mobile network service before enabling MUP. The PEs S1, S2, and S3 compose an SR network. A routing instance is configured to each network of the mobile service. N6DN in S1 and S2 are providing connectivity to edge servers and the Internet respectively.

VRF (Virtual Routing Forwarding) is the routing instance to accommodate MUP segments in this section. All example cases in this section follow the typical routing policy control using the BGP extended community described in [RFC4360] and [RFC4684]

```
  __ N3   /-----------+-----+------------\
 /  \RAN /            |MUP-C|             \
/ V/v\_  |            +-----+             | N6   __
\    / \ |----+                     +----| DN  /  \
 \__/   \| S1 |                     | S2 |----/W/w \
  __    /|----+                     +----|    \    /
 /  \__/ |             +----+             |     \__/
/ E/e\N6 \             | S3 |             /
\   /DN   \------------+----+------------/
 \__/             N3UPF  /\ N6UPF
                    X/x /  \ Y/y
                      +-----+
                      | UPF |
                      +-----+
```

Figure 2

The following routing instances are configured:

* N3RAN in S1
    - export route V/v with route-target (RT) community C1
    - import routes which have route-target (RT) community C1 and C2
* N6DN in S1
    - export route E/e with RT C4
    - import routes which have RT C3 and C4
* N6DN in S2
    - export route W/w with RT C4
    - import routes which have RT C3 and C4
* N3UPF in S3
    - export route X/x with RT C2
    - import routes which have RT C1

* N6UPF in S3

  - export route Y/y with RT C3

  - import routes which have RT C4

Note: The above configurations are just to provide typical IP connectivity for 3GPP 5G. When the above configurations have been done, each endpoint in V/v and X/x can communicate through S1 and S3, but they can not communicate with nodes in E/e, W/w and Y/y.

7.2. MUP PE Deployment at All SR Domain Edges

Here, the PEs S1, S2 and S3 are configured to enable MUP as follows:

* S1

  - advertises Interwork type discovery route: V/v with SID S1::

  - set S1:: behavior End.M.GTP4.E or End.M.GTP6.E

* S1

  - advertise Direct type discovery route: MUP Direct Segment community D1 and SID S1:1::

  - set S1:1:: behavior End.DT4 or End.DT6 for the N6DN in S1

* S2

  - advertise Direct type route: MUP Direct Segment community D1 and SID S2::

  - set S2:: behavior End.DT4 or End.DT6 for the N6DN in S2

S1 adopts the local N6DN to prioritize the closer segment for the same Direct Segment. Another PE may adopt D1 from S2, if the PE has no local N6DN for D1 and closer to S2 than S1.

```
                                   U1
                                    |
         U/u                        v
           \__ N3   /-----------+-----+------------\
           /  \RAN /            |MUP-C|             \
          / V/v\_  |            +-----+              | N6   __
          \    / \ |----+                      +----| DN  /  \
           \__/   \| S1 |                      | S2 |----/W/w \
            __    /|----+                      +----|     \    /
           /  \__/ |             +----+              |      \__/
          / E/e\N6 \             | S3 |             /
          \    /DN  \------------+----+------------/
           \__/             N3UPF  /\ N6UPF
                              X/x /  \ Y/y
                                +-----+
                                | UPF |
                                +-----+
```

Figure 3

Now, session information U1 is put to a MUP Controller, MUP-C, and MUP-C is configured to transform U1 to the routes as follows:

* MUP-C

  - attach the MUP Direct Segment ID D1 and RT C3 to the DN in U1

  - transforms UE’s prefix U/u, the F-TEID on access side (gNB) and QFI in U1 to the Type 1 session transformed route for the prefix U/u with the F-TEID, the QFI, and RT C3

  - transforms F-TEID on core side (UPF) X in U1 to the Type 2 session transformed route for X with MUP segment-ID D1 and RT C2

Then N3RAN and N6DN import route X and U/u respectively. S1 and S2 resolves U/u’s remote endpoint with V/v and then install SID S1:: for U/u in FIB. S1:: will not appear in the packet from E/e to U/u over the wire.

As S1 adopts local N6DN for D1, N3RAN in S1 decapsulates GTP-U packets from V/v to X and then lookup the inner packets from U/u in N6DN after the decapsulation.

Note: When the above configurations have been done, MUP is applied only to the packets from/to U/u. Each endpoint in U/u, W/w and E/e can communicate through S1 and S2. The rest of traffic from/to other UEs go through the usual 3GPP 5G user plane path using UPF via S3.

7.3. Adding Direct Segment with New MUP PE

Another case shown in Figure 4 is that S4 joins the SR network and accommodates edge servers in the N6DN in S4.

```
                                   U1
                                    |
          U/u                       v                       __
            \__ N3   /-----------+-----+------------\      /  \
            /  \RAN /            |MUP-C|             \  __/W/w \
           / V/v\_  |            +-----+        +----|_/N6\    /
           \    / \ |----+                      | S2 |  DN \__/
            \__/   \| S1 |                      +----|      __
             __    /|----+                      +----|_    /  \
            /  \__/ |             +----+        | S4 | \__/E/e \
           /    \N6 \             | S3 |        +----/  N6\    /
           \    /DN  \------------+----+------------/   DN \__/
            \__/             N3UPF  /\ N6UPF
                               X/x /  \ Y/y
                                 +-----+
                                 | UPF |
                                 +-----+
```

Figure 4

The following routing instances are configured:

* N3RAN in S1 (same with the previous case)

   - export route V/v with RT C1

   - import routes which have RT C1 and C2

* N6DN in S1

   - export no route

   - import routes which have RT C4

* N6DN in S2 (same with the previous case)

   - export route W/w with RT C4

- import routes which have RT C3 and C4

* N3UPF in S3 (same with the previous case)

  - export route X/x with RT C2

  - import routes which have RT C1

* N6UPF in S3 (same with the previous case)

  - export route Y/y with RT C3

  - import routes which have RT C4

* N6DN in S4

  - export route E/e with RT C4

  - import routes which have RT C3 and C4

Here, the PEs are configured to enable MUP as following:

* S1 (same with the previous case)

  - advertises Interwork type route: V/v with SID S1::

  - set S1:: behavior End.M.GTP4.E or End.M.GTP6.E

* S1

  - advertise Direct type route: MUP Direct Segment community D1 for the local N6DN

  - set S1:1:: behavior End.DT4 or End.DT6 for the N6DN in S1

* S2 (same with the previous case)

  - advertise Direct type route: MUP Direct Segment community D1 and SID S2::

  - set S2:: behavior End.DT4 or End.DT6 for the N6DN in S2

* S4

  - advertise Direct type route: MUP Direct Segment community D2 and SID S4::

  - set S4:: behavior End.DT4 or End.DT6 for the N6DN in S4

As in the previous case, S1 adopts the local N6DN for D1 as long as S1 prioritizes the closer segment for the same MUP Direct Segment. The Direct type route from S4 for D2 with SID S4:: will be kept in S1.

* MUP-C (same with the previous case)

  - attach the MUP Direct Segment ID D1 and RT C3 to the DN in U1

  - transforms UE's prefix U/u, the F-TEID on access side (gNB) and QFI in U1 to the Type 1 session transformed route for the prefix U/u with the F-TEID, the QFI, and RT C3

  - transforms F-TEID on core side (UPF) X in U1 to the Type 2 session transformed route for X with MUP Direct Segment community D1 and RT C2

Then N3RAN and N6DN import route X and U/u respectively. S2 and S4 resolve U/u's remote endpoint with V/v and then install SID S1:: for U/u in FIB.

As in the previous case, S1 adopts local N6DN for D1, N3RAN in S1 decapsulates GTP-U packets from V/v to X and then lookup the inner packets from U/u in N6DN after the decapsulation.

For D2 on the other hand, no corresponding N6DN existed in S1. However, E/e with RT C4 from S4 is imported into N6DN in S1 as a VPN route, E/e is reachable from U/u via N6DN for D1 in S1.

If a session U1' includes the DN corresponding to D2, MUP-C advertises Type 2 session transformed route X' with MUP Direct Segment community D2, and then N3RAN in S1 instantiates H.M.GTP4.D or End.M.GTP6.D for X with S4:: as the last SID in the received Direct type route from S4.

Note: When the above configurations have been done, MUP is applied only to the packets from/to U/u. Each endpoint in U/u, W/w and E/e can communicate through S1, S2 and S4. The rest of traffic from/to other UEs go through the usual 3GPP 5G user plane path using UPF via S3.

7.4. Collapsed MUP PE Deployment

In this case only S1 enables MUP in a collapsed fashion. S2 and S3 are L3VPN PEs without MUP capability. In this section, S2 and S3 are illustrated as SRv6 nodes. But they can be non-SR nodes if S1 provides SR independent connectivity to S2 and S3.

```
                                   U1
                                    |
          U/u                       v
            \__ N3   /-----------+-----+------------\
            /  \RAN /           |MUP-C|             \
           / V/v\_  |           +-----+             | N6   __
           \    / \ |----+                     +----| DN  /  \
            \__/   \| S1 |                     | S2 |----/W/w \
             __    /|----+                     +----|    \    /
            /  \__/ |             +----+            |     \__/
           / E/e\N6 \             | S3 |            /
           \    /DN  \------------+----+------------/
            \__/             N3UPF  /\ N6UPF
                               X/x /  \ Y/y
                                 +-----+
                                 | UPF |
                                 +-----+
```

Figure 5

The difference between the previous case in Section 7.1 for the routing instance configuration is following:

* N6DN in S1

   - export route E/e with RT C4

   - import routes which have RT C3, C4 and C5

Here, S1 is configured to enable MUP and S2 as an L3VPN PE is configured as follows:

* S1

   - may not advertise Interwork type discovery route for V/v

   - may not advertise Direct type discovery route with MUP Direct Segment community D1 and S1:1::

   - set S1:1:: behavior End.DT4 or End.DT6 for the N6DN in S1

* S2

   - set S2:: behavior End.DT4 or End.DT6 for the N6DN in S2

Now, session information U1 is added to the MUP Controller, MUP-C, and MUP-C and S1 is configured to transform U1 to the routes as follows:

* MUP-C

  - attach the MUP Direct Segment ID D1 and RT C5 to the DN in U1

  - transforms UE's prefix U/u, the F-TEID on access side (gNB) and QFI in U1 to the Type 1 session transformed route for the prefix U/u with the F-TEID, the QFI, and RT C5

  - transforms F-TEID on core side (UPF) X in U1 to the Type 2 session transformed route for X with MUP Direct Segment community D1 and RT C2

* S1

  - advertises U/u as an L3VPN route with RT C4 and SID S1:1::, when the Type 1 session transformed route is imported into the N6DN

Then the N3RAN and N6DN import route X and U/u respectively. S1 resolves U/u's remote endpoint with V/v and then create the corresponding GTP encap entry for U/u into the N3RAN FIB. S2 will create a regular L3VPN routing entry for U/u with SID S1:1:: in the N6DN when S2 imports the L3VPN route with RT C4 for U/u advertised from S1.

As S1 adopts local N6DN for D1, N3RAN in S1 decapsulates GTP-U packets from V/v to X and then lookup the inner packets from U/u in N6DN after the decapsulation.

Note: When the above configurations have been done, MUP is applied only to the packets from/to U/u. Each endpoint in U/u, W/w and E/e can communicate through S1 and S2. The rest of traffic from/to other UEs go through the usual 3GPP 5G user plane path using UPF via S3.

8. IANA Considerations

This memo includes no request to IANA.

9. Security Considerations

TBD.

10. References

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User Plane Message Encoding
draft-murakami-dmm-user-plane-message-encoding-05

Abstract

This document defines the encoding of User Plane messages into Segment Routing Header (SRH). The SRH carries the User Plane messages over SRv6 Network.

Status of This Memo

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1. Introduction

3GPP defines User Plane function (UPF) and the protocol messages that it supports. The User Plane messages support in-band signalling for path and tunnel management. Currently, User Plane messages are defined in TS 29.281 [TS29281].

When applying SRv6 (Segment Routing IPv6) to the user plane of mobile networks, based on draft-ietf-dmm-srv6-mobile-uplane [I-D.ietf-dmm-srv6-mobile-uplane]. User Plane messages must be carried over SRv6 network. This document defines which User Plane message must be encoded to SRv6 and also defines how to encode the User Plane messages into SRH.

In addition, SRH is mandatory at the ultimate segment upon carrying the User Plane messages because User Plane message is encoded into SRH. Hence, this document considers how to deal with the encoding of User Plane messages into SRH when PSP is applied that SRH is popped out at the penultimate segment.

2. Requirements Language

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].

3. Conventions and Terminology

SRv6: Segment Routing IPv6.

GTP-U: GPRS Tunneling Protocol User Plane.

UPF: User Plane Function.

SRH: IPv6 Segment Routing Header.

PSP: Penultimate Segment POP of the SRH.

USP: Ultimate Segment Pop of the SRH.

4. Motivation

3GPP User Plane needs to support the user plane messages associated with a GTP-U tunnel defined in [TS29281]. In the case of SRv6 User Plane [I-D.ietf-dmm-srv6-mobile-uplane], those messages are also required when the user plane interworks with GTP-U.

IPv6 Segment Routing Header (SRH) [RFC8754] is used for SRv6 User Plane. SRH is able to associate additional information to the segments. The Tag field of SRH is capable to indicate different properties within a SID. SRH TLV is capable to provide meta-data to the endpoint node.

The above capability of SRH motivates us to map the user plane messages into it because of the same encapsulation with the packets of carrying client packets. It introduces no additional headers or extension headers to be chained in the packet just for carrying the user plane messages.

5. User Plane Message encoding into SRH

This section defines how to encode the User Plane messages into SRH in order to carry the User Plane messages over SRv6 network.

5.1. GTP-U Header format

3GPP defines GTP-U Header format as shown below.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Ver |P|R|E|S|N| Message Type  |            Length             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                Tunnel Endpoint Identifier                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Sequence Number          | N-PDU Number  |  Next-Ext-Hdr |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 1: GTP-U Header format

User Plane message type is encoded in Message Type field of GTP-U Header. The following User Plane messages must be carried over SRv6 network at least. The value of each User Plane message type is defined as shown below.

Echo Request: 1

Echo Reply: 2

Error Indication: 26

End Marker: 254

5.2. Args.Mob.Upmsg

draft-ietf-dmm-srv6-mobile-uplane [I-D.ietf-dmm-srv6-mobile-uplane] defines the format of Args.Mob.Session argument which is used in SRv6 SID Mobility Functions in order to carry the PDU Session identifier. The format of Args.Mobs.Session is defined as shown below.

```
  0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   QFI     |R|U|                PDU Session ID                 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|PDU Sess(cont')|
+-+-+-+-+-+-+-+-+
```

Figure 2: Args.Mob.Session format

In case of Echo Request, Echo Reply and Error Indication, Sequence Number in GTP-U header needs to be carried. Similar to draft-ietf-dmm-srv6-mobile-uplane [I-D.ietf-dmm-srv6-mobile-uplane], the new arguments to carry Sequqnce number for Echo Request, Echo Reply and Error Indication message needs to be defined. For this, the following Args.Mobs.Upmsg should be defined newly to carry Sequence number.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   QFI     |R|U|       Sequence Number         |      Pad      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Pad(cont')  |
+-+-+-+-+-+-+-+-+
```

Figure 3: Args.Mob.Upmsg format for Echo Request, Echo Reply and Error Indication

QFI bit, R bit, U bit and 16-bit Sequence Number is encoded in Args.Mobs.Upmsg. The remaining bits followed by Sequence Number must be padded in 0.

In case of End Marker, TEID shall be used as PDU Session ID same as draft-ietf-dmm-srv6-mobile-uplane [I-D.ietf-dmm-srv6-mobile-uplane]. Hence, for End Marker, Args.Mobs.Session should be used to carry TEID as PDU Session ID.

5.3. Encoding of Tags Field

The Segment Routing Header is defined in IPv6 Segment Routing Header (SRH) [RFC8754]. This draft defines 16 bits Tag field but does not define the format or use of this Tag field in the Segment Routing Header.

The User Plane message type encoding is defined in TS 29.281 [TS29281]. Based on this definition, the User Plane message type must be encoded into the Tag field in the Segment Routing Header in order to indicate the type of the user plane messages for at least Echo Request, Echo Reply, Error Indication or End Marker.

Only UPF must process the Tag field where the user plane message is encoded. In addition, when the user plane message is encoded in the Tag field, the UPF should not encode any segments in the Segment Routing Header whose function modifies the Tag field value. Any other transport router implementing SRv6 must ignore the Tag field upon processing the Segment Routing Header.

The user plane messages must be encoded into the Tag filed as shown below.

```
 0                             1
 0  1  2  3  4  5  6  7  8  9  0  1  2  3  4  5  6
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|         Reserved                     |B3|B2|B1|B0|
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
```

Figure 4: Tag Field Encoding

Bit 0 [B0]:   End Marker

Bit 1 [B1]:   Error Indication

Bit 2 [B2]:   Echo Request

Bit 3 [B3]:   Echo Reply

End Marker, Echo Request and Echo reply messages do not require any additional information elements. However, Error Indication message requires the additional information elements like Tunnel Endpoint Identifier Data IE, GSN Address, etc. These additional information elements can be encoded into the SRH TLV that is defined in the next section.

5.4. User Plane message Information Element Support

End Maker, Echo Request and Echo Reply messages do not require any additional information elements. However, Error Indication message requires additional 3GPP IEs (Information Element). These additional information elements must be carried over SRv6 network as well. However SRv6 SID has limited space only. Hence it cannot carry a lot of information elements.

In order to carry more information elements, SRH TLV shall be leveraged. SRH TLV is defined in IPv6 Segment Routing Header (SRH) [RFC8754] in order to carry the meta-data for the segment processing. In order to carry additional User Plane messages like 3GPP IEs, the new type named as "User Plane Container" must be defined as the new SRH TLV. The "User Plane Container" can carry additional User Plane messages which includes multiple 3GPP IEs with 1 sub-TLV.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Type     |      Length       |  User Plane message sub-TLV |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
//               User Plane message sub-TLV                     //
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

User Plane Container TLV

Type: to be assigned by IANA

Length: Length of User Plane message sub-TLV

User Plane message sub-TLV: User Plane message sub-TLV defined below

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Type     |      Length       |            Value           //
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

User Plane message sub-TLV

Type: Type of User Plane message sub-TLV

3GPP IE sub-TLV: 0x01

Length: Length of Value

Value: User Plane Message data

3GPP IE sub-TLV: multiple 3GG IEs

5.5. SID flavor consideration

This section considers SID flavor of where the SRH is popped out at either the penultimate or the ultimate segment.

In order to carry User Plane message over SRv6 network, SRH must be sustained over entire SRv6 network because User Plane message type and required information elements are encoded into SRH. If the penultimate segment is popping out SRH, i.e., PSP, User Plane message can not be carried in entire SRv6 network.

In order to avoid this problem, USP is recommended in SRv6 Mobile network. In this case, SRH is never popped out and User Plane message can be sustained over entire SRv6 network.

However, if PSP needs to be enabled in SRv6 network, it is also a possible solution to encap another SRH which carries User Plane message along with the outer IPv6 or SRH.

6. Security Considerations

This document does not raise any additional security issues. This document just define the mechanisms for mapping between user plane message (GTP-U message) and SRH in SRv6. Basically, since this document is using SRH defined in [RFC8754] to carry user plane message, same security consideration stated in [RFC8754] shall be applied.

7. IANA Consideration

The type value of SRH TLV for User Plane Container must be assigned by IANA.

8. Acknowledgements

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Intended status: Standards Track   Futurewei Technologies, Inc.
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OSPF Monitor Node
draft-retana-lsr-ospf-monitor-node-00

Abstract

This document specifies mechanisms that allow a node to monitor an OSPF network actively without influencing the topology or affecting its stability.

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1. Introduction

Monitoring the control plane activity in a network is essential to designing and maintaining a robust and stable network. Passive (listen- only) devices deployed in broadcast or non-broadcast multi-access (NBMA) networks have typically satisfied the need. However, passive devices depend on more than two routers being present in the network and are not visible to the network operator -- anyone can listen.

An alternative implementation, primarily used in point-to-point interfaces, or in cases where the listening device is the only other node on the interface, is to participate fully in the protocol: create a full adjacency with the closest router, participate in designated router (DR) election, etc. The node is now visible in the network, can advertise control plane information, and any changes in its status are flooded throughout the network. Many link state advertisements (LSA) or state changes can cause instability in the network, and additional configuration is usually needed to avoid the device becoming a transit node.

This document specifies mechanisms that allow a node to monitor OSPF activity without influencing the topology or affecting its stability while being fully adjacent and known to the network operator. These nodes are referred to as a Monitor Node. Two such mechanisms are introduced:

Section 3 describes a local implementation to be used in the case where the Monitor Node is the only other router on an interface.

Section 4 specifies signaling in the Hello message for a node to communicate its intention to become a Monitor Node.

The mechanisms presented apply to both OSPFv2 [RFC2328] and OSPFv3 [RFC5340]. The term OSPF is used to refer to both versions.

1.1. 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.

2. Router Interface Parameters

This document defines the following router interface configurable parameters:

DoNotAdvertiseLink
: Indicates whether or not the link is advertised on the local router-LSA. If set to "enabled," the router MUST NOT include a corresponding interface description in its router-LSA. The router MUST NOT originate other LSAs related to the link or its addresses. Enabling this interface parameter overrides the setting of LinkLSASuppression [RFC5340].

DoNotRequestAndIgnoreLSAs
: Indicates whether or not the router should request and use LSAs from other routers on this interface. If set to "enabled," the router MUST consider its Link state request list empty. Also, the router MUST consider the LS age of any received LSA to be equal to MaxAge and process it according to Section 13 of [RFC2328].

3. Monitoring Interface

By using the interface parameters specified in Section 2, a router can treat all neighbors on the interface as Monitor Nodes. To do so, DoNotAdvertiseLink and DoNotRequestAndIgnoreLSAs SHOULD be configured simultaneously. If either parameter is configured on a broadcast or NBMA interface, the router MUST NOT participate in the Designated Router (DR) selection process.

Enabling DoNotAdvertiseLink by itself results in any LSAs originated by the Monitor Node not being resolved in the routing table.

If only DoNotRequestAndIgnoreLSAs is enabled, the router MUST treat the link as a stub network. Note that the neighbor information (corresponding to the Monitor Node) is not advertised.

4. The Monitor Node Option

This document defines a new Option in the Extended Options and Flags (EOF) Link-Local Signaling (LLS) TLV [RFC5613]. The new option is called Monitor (M-bit) and has a value of TBD.

When set, the M-bit indicates that the originating router is a Monitor Node. Other routers on the same link MUST:

* Consider the Monitor Node ineligible for the DR selection process.

* Consider its Link state request list empty with respect to the Monitor Node.

* Consider the LS age of any LSA received from the Monitor Node is equal to MaxAge.

If the Monitor Node is one of only two routers on an interface, the other router MUST NOT include a corresponding interface description in its router-LSA. Furthermore, other LSAs related to the link or its addresses MUST NOT be originated. This situation overrides the setting of LinkLSASuppression.

5. Operational Considerations

The use of the monitoring interface (Section 3) applies to all other routers on the same interface. While the Monitor Node option (Section 4) applies to only the router signaling the M-bit. Network administrators should use the Monitor Node option in transit interfaces where one router is a Monitor Node.

If the Monitor Node is the only other router on an interface, the link information can be advertised (as a stub link) if only DoNotRequestAndIgnoreLSAs is enabled.

The deployment of the Monitoring Interface (Section 3) requires that only the non-Monitor Node supports this specification. On the other hand, the Monitor Node Option (Section 4) requires all nodes on the interface to support the functionality. If support is not present in all the routers on the link, the Monitor Node will be eligible to be a DR, and its information may be flooded through the network.

6. Acknowledgements

TBD

7. IANA Considerations

IANA is requested to allocate a value (TBD) from the "LLS Type 1 Extended Options and Flags" registry for the M-bit (Section 4).

8. Security Considerations

The security considerations documented in [RFC2328], [RFC5340], and [RFC5613] apply to this extension.

This document defines a new type of node, called a Monitor Node, intended only to receive information from its neighbors and not send any. If the LSAs from the Monitor Node are not ignored, they will be flooded throughout the network. A rouge Monitor Node may advertise LSAs with an Advertising Router field that doesn’t correspond to its router ID. This type of vulnerability is not new, but it is already present in the base specification.

Even though it is expected that the local network operator deploys any Monitor Node, authentication mechanisms such as those specified in [RFC5709], [RFC7474], [RFC4552], or [RFC7166] SHOULD be used.

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5G Distributed UPFs for 5G Multicast and Broadcast Services (5MBS)
draft-tjiang-dmm-5g-dupf-5mbs-01

Abstract

The drafts [I-D.zzhang-dmm-5g-distributed-upf] and [I-D.zzhang-dmm-mup-evolution] have described the 5G mobile user plane (MUP) via the refinement of distributed UPFs and a more radical proposal by integrating gNB & UPF as a single network function (NF). Some user plane implementation requirements that vendors and operators are exploring are not introducing changes to 3GPP architecture & signaling, if possible. The document 3GPP TS 23.247 [_3GPP-23.247] for 5G multicast and broadcast services, or 5MBS, specifies the 5GS architecture to support MBS communication. Thanks to the addition of new 5GS network functions (NFs) and MB-interfaces on 5G CP & UP, specifically if coupled with the increasingly popular satellite-related requirements, these would certainly post additional provisioning & implementation challenges to the underlay transport infrastructure.

This document is not an attempt to do 3GPP SDO work in IETF. Instead, it discusses how to potentially integrate distributed UPFs with the delivery of 5MBS communication, as well as the benefits of using distributed UPFs to handle 5MBS traffic delivery.

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1. Distributed UPFs in 5G User Plane

Mobile User Plane (MUP) in 5G has two distinct parts: the Access Network part between UE and gNB, and the Core Network part between gNB and UPF. UPFs are traditionally deployed at central locations, with UEs' PDU sessions encapsulated and extended thru GTP-U tunnels via the N3 (and potentially N9) interfaces in 5GS. The interface N6 supports fundamentally a direct IP or Ethernet connection to the data network or DNN.

Actually, UPFs could be distributed & deployed closer to gNBs. The draft [I-D.zzhang-dmm-5g-distributed-upf] has described the 5G mobile user plane (MUP) via the refinement of distributed UPFs or dUPFs. The following picture shows the dUPF architecture:

```
                          N3             N6
       UE1         gNB1    |     dUPF1     |
    +---------+            |+------+-----+|
    |   PDU   |            || PDU  |     ||       PE1
    +---------+ +------+------+|+-------+ IP/ ||     +-----+--+
    |         | |      |GTP-U ||GTP-U |     ||----+ IP/ |  |
    | 5G-AN   | |5G-AN +-------+|+-------+Ether||     |Ether|  |
    | xHaul   | |xHaul |L3/2/1||L3/2/1|     ||     +-----+--+
    +---------+ +------|------+|+------------+|    (          )
                               |              |   ( Transport  )  PE3
                               |              |   (  Network   +--+-----+
       UE2         gNB2        |     dUPF2    |   (            |  | IP/ |
    +---------+                |+------+-----+|   (   (DN)     |  |Ether|
    |   PDU   |                || PDU  |     ||    (           +--+-----+
    +---------+ +------+------+|+-------+ IP/ ||     +-----+--+
    |         | |      |GTP-U ||GTP-U |     ||     | IP/ |  |
    | 5G-AN   | |5G-AN +-------+|+-------+Ether||     |Ether|  |
    | xHaul   | |xHaul |L3/2/1||L3/2/1|     ||     +-----+--+
    +---------+ +-------------+|+------------+|      PE2
```

In distributed UPF architecture, the central (PSA) UPF is no longer needed. dUPF1 and UPF2 connect via PE1 and PE2, respectively, to the DN VPN (or network instance/NI) that UE1 and UE2 intend to access. There could exist other PEs, like PE3 in the picture, for other sites of the same network domain(VPN or NI) or for global Internet access.

There are some benefits of distributed UPFs:

* The N3 interface becomes very simple - over a direct or short transport connection between gNB and dUPF.

* The transport infrastructure off N3/N9 and N6 are straightforward, most likely over the same underlay VPN (MPLS, SR-MPLS or SRv6) supporting the traditional N3/N9 tunneling as in centralized PSA UPF case.

* MEC becomes much simpler since no need to deploy centralized PSA UPF plus ULCL UPFs; UE-UE traffic can be optimized for LAN-type services (via host-route).

In short, the distributed UPFs model achieves "N3/N9/N6 shortcut and central UPF bypass", which is desired by many operators.

2. 5G Multicast and Broadcast Services (5MBS)

The 3GPP document TS 23.247 [_3GPP-23.247] for 5G multicast and broadcast services, or 5MBS, specifies the 5GS architecture to support MBS communication. The following picture shows the brief system architecture of 5MBS:

```
                ----+----------(SBA for 5GC) ---------+-----
                    |          |                      |
                 +--+--+   +---+---+              +---+----+
                 | AMF |   |  SMF  |              | MB-SMF |
                 +--+--+   +-+-+-+-+              +---+----+
                   /           |                      |
               N2 /         N4 |                  N4mb|
                 /             |                      |
                /    N3    +-+-+---+     N19mb    +---+----+ N6mb +----+
           +-----+---------+  UPF  +--------------| MB-UPF |------| DN |
  +----+   |     |         +-------+ (Individual) +---+----+      +----+
  | UE +---+ gNB |                                    |
  +----+   +-----+                                    |
                 |_________N3mb (shared delivery)_____|
```

TS 23.247 [_3GPP-23.247] adds new 5GS network functions (NFs) on both 5G control-plane (CP) and user-plane (UP). For example, the CP NF MB-SMF is, in collaboration with the regular SMF, to provision and signal to the UP NF MB-UPF (via the interface N4mb) for setting up MBS delivery path.

5MBS has specified two data delivery modes, individual delivery vs. shared delivery:

* Individual delivery: When the (downlink or DL) MBS packets are received by the MB-UPF from the interface N6mb, MB-UPF replicates & forwards those packets towards (multiple) UPFs, via the interface N19mb, through either unicast (requiring multiple GTP tunnels if unicast underlay transport is applied) or multicast (if multicast underlay transport over N19mb is applied) transmission.

* Shared delivery: When the (DL) MBS packets are received by the MB-UPF from N6mb, MB-UPF replicates & forwards those packets towards (multiple) gNBs, via the interface N3mb (the lower-path in the picture), through either (multiple) separate GTP tunnels if unicast underlay transport over N3mb is applied, or a single GTP tunnel if multicast underlay over N3mb is supported.

3. Challenges in 5G MBS Communication

3.1. 5MBS Transport Challenges

The 5MBS architecture in TS 23.247 [_3GPP-23.247] introduces some network challenges:

* Because of the addition of new CP and UP NFs, this will post additional provisioning & implementation challenges to the underlay transport infrastructure. For example, in the individual delivery mode, both SMF and MB-SMF have to synchronize with each other to help set up the relay/stitching path between UPF, MB-UPF and DN.

* The picture in previous section shows three new interface types corresponding to three different segments: N3mb, N6mb and N19mb. Based on the traffic delivery mode, once MB-UPF receives DL traffic from N6mb, it will have to do either individual or shared delivery.

* In accordance with TS 23.247 [_3GPP-23.247], the underlay transport infrastructure of all three segments can use either unicast or multicast transmission, based on the capabilities of underlay networks. For example, for the DL _shared_ delivery from MB-UPF to gNB via the interface N3mb, 5G MBS packets can be transmitted to multiple gNBs via multicast transmission if the underlay network supports. Otherwise, MB-UPF will have to use unicast to transmit separately to (multiple) gNBs. Considering that this unicast/multicast flexibility is applicable to all the three above-mentioned segments, the implementation will have to face more challenges.

3.2. 5MBS UP Signaling Challenges

The user plane from the MB-UPF to gNB directly (i.e., the lower-path in the above figure for the shared delivery) and the user plane from the MB-UPF to UPFs then to gNB (i.e., the upper path in the figure for individual delivery) may use IP multicast transport via a common GTP-U tunnel per MBS session, or use unicast transport via separate GTP-U tunnels at gNB or at UPF per MBS session. When using the IP multicast transport, GTP-U Multicast Tunnels shall be used for unidirectional transfer of the encapsulated T-PDUs from one GTP-U Tunnel Endpoint (i.e., acting as the sender) to multiple GTP-U Tunnel Endpoints (i.e., acting as receivers). The Common Tunnel Endpoint ID (C-TEID) which is present in the GTP header shall indicate which tunnel a particular T-PDU belongs to. The C-TEID value to be used in the TEID field shall be allocated at the source Tunnel Endpoint (e.g., the sender) and signaled to the destination Tunnel Endpoints (e.g., receivers) using a control plane protocol, e.g., GTPv1-C & GTPv2-C. One C-TEID shall be allocated per MBMS bearer service or per MBS session [_3GPP-23.247][_3GPP-29.281]. As we have explained in the draft [I-D.zzhang-dmm-mup-evolution], the signaling overhead to establish a N3 GTP unicast tunnel has reached seven steps, let alone the case of the more complicated MBS tunnel creation.

3.3. 5MBS Challenges in Satellite Communication

The 5G service via the satellite constellation has become a popular topic in 3GPP. There are currently three major satellite-related projects in SA workgroups, i.e., the satellite access (SAT_Ph2) [_3GPP-23.700-28] and the satellite backhaul (SATB) [_3GPP-23.700-27] in SA2 as well as the Phase-3 enhancement via the satellite-based store-and-forward technology (SAT_Ph3) in SA1 WG [_3GPP-22.865]. These projects study various 5GS requirements when either a gNB or a UPF or both are on-board satellites. Evidently, the continuously-moving satellite constellations introduce another dimension of challenges to UE registration, session management and traffic routing. The GTP-U tunnel end points have to be changed frequently when the satellite providing the on-board service for a UPF rotates away from the corresponding gNB of the same GTP-U tunnel. For the SAT_access case, the ground station (GS) has to find a new gNB on-board another satellite every couple of minutes (e.g., being around 7-8 minutes for the LEO category) to hand over UEs. There are significantly large amount of singalling messages involved even for unicast case via satellite constellation, let alone if we extend the similar scenarios to 5G MBS communication.

4. 5G Distributed UPF for 5G MBS Implementation

The REQ8 of [RFC7333] talks about the multicast efficiency between non-optimal and optimal routes, where it states that, in term of multicast considerations, DMM SHOULD enable multicast solutions to be developed to avoid network inefficiency in multicast traffic delivery.

The current 5MBS architecture requires all DL multicast traffic go through the (centralized) MB-UPF, regardless of using the individual or shared delivery. In many operators' networks, 5GS might be deployed in a location that is distant from customer sites. If the deployed site happens to be on-board satellites, the additional complexities and moving dynamics will certainly worsen the operations. In these scenarios, the efficiency of multicast transmission will be compromised. On the other aspect, a 5G dUPF deployed closer to gNB, or even more radically applying 'ANUP' via the possible integration of gNB & UPF [I-D.zzhang-dmm-mup-evolution], might lead to more efficient implementation:

* For shared delivery, the MB-UPF can be distributed closer to or integrated with gNB, i.e., either dUPF or ANUP-like. The N6mb is a normal IP interface which is connected to DN over underlay network. This transport connection will most likely use the VPN infrastructure that has been provisioned by operators for 5GS. As a dUPF or ANUP, the N3mb tunnel off MB-UPF could be made much simpler. In some field edge sites, a dUPF could co-locate on-prem with gNB, which can even remove the usage of complex (inter-site) VPN to favor native IP transport.

* For individual delivery, it involves two UPFs, one regular UPF and one MB-UPF. To follow the current 3GPP specification, we can distribute and deploy both UPFs closer to gNB. While the DL traffic off the N6mb interface may achieve the same gain as in the shared-delivery mode, the transport for the N19mb tunnel and the (regular) N3 tunnel can be significantly simplified. Remember we have mentioned previously that either unicast or multicast (underlay) transmission can be used for N19mb (and actually also for N6mb and N3mb). Therefore, applying dUPF or, possibly ANUP in future, will help simplify the N19mb VPN transmission.

* For individual delivery, if we expand the scope beyond the current 3GPP spec., e.g., looking beyond the 5G or even 6G roadmap that are already on the horizon of the 3GPP planning, we could integrate the regular UPF and MB-UPF together as a distributed UPF, and then deploy the dUPF closer to gNB. Of course, we might even take one step further by integrating both UPFs (UPF and MB-UPF) and gNB as a single 'logical' node, i.e., ANUP [I-D.zzhang-dmm-mup-evolution]. Regardless, in either scenario, both the N19mb and N3 tunnels can be simplified, or even consolidated, significantly, TS 23.247 [_3GPP-23.247] specifies the behaviors of MB-UPF, as a standalone NF. Indeed, all the features and behaviors that would be implemented by a MB-UPF can be collaboratively integrated into a regular UPF. This type of 'merging' should lead to more network efficiency and better multicast traffic forwarding, conforming to the [RFC7333] REQ8.

When we take into consideration the above plausible arguments and accordingly apply them to different 3GPP satellite-related projects, e.g., SATB (backhaul), SAT_Ph2 & SAT_Ph3 (access), we can certainly draw the conclusion that the extra burden of signalling messages, the complexity of control plane as well as the excessive encapsulations of user plane, as introduced by 5MBS, can be relieved dramatically.

Both drafts [I-D.zzhang-dmm-5g-distributed-upf] [I-D.zzhang-dmm-mup-evolution] discussed and compared briefly different tunneling mechanisms to implement the 3GPP GTP-U UP, i.e., SRv6, MPLS as the underlay, or in [I-D.mhkk-dmm-srv6mup-architecture] specifying a new SRv6 based MUP architecture to replace the GTP-U. While these proposals may experience different issues upon 5MBS transport implementation, the application of distributed or 'integrated' UPF might make it more feasible.

5. Security Considerations

TBD.

6. IANA Considerations

This document requests no IANA actions.

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5G Distributed UPFs
draft-zzhang-dmm-5g-distributed-upf-01

Abstract

This document describes evolution of mobile user plane in 5G, including distributed UPFs and alternative user plane implementations that some vendors/operators are pushing without changing 3GPP architecture/signaling. This also sets the stage for discussions in a companion document about potentially integrating UPF and Acess Node (AN) in a future generation (xG) of mobile network.

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1. Current User Plane in 5G

Mobile User Plane (MUP) in 5G [_3GPP-23.501] has two distinct parts: the Access Network part between UE and AN/gNB, and the Core Network part between AN/gNB and UPF.

```
                              N3              N9             N6
       UE          AN(gNB)    |    I-UPF      |  PSA UPF     |
   +---------+                |               |              |
   |App Layer|                |               |    routing   |    __
   +---------+                |               |+--/---+---\-+|   (  )
   |PDU Layer|      relay     |     relay     || PDU  |     ||  (    )
   +---------+ +---/--+--\---+|+---/--+--\---+|+------+IP+L2|| (      )
   |         | |      |GTP-U |||GTP-U |GTP-U |||GTP-U |     || (  DN  )
   | 5G-AN   | |5G-AN +------+||------+------+||------+  or || (      )
   |         | |      |UDP+IP|||UDP+IP|UDP+IP|||UDP+IP|     ||  (    )
   | Proto   | |Proto +------+||------+------+||------+Ether||   (  )
   |         | |      |  L2  |||  L2  |  L2  |||  L2  |     ||    --
   | Layers  | |Layers+------+||------+------+||------+-----+|
   |         | |      |  L1  |||  L1  |  L1  |||  L1  | L1  ||
   +---------+ +------+------+|+------+------+|+------+-----+|
                              |               |              |
```

For the core network (CN) part, N3 interface extends the PDU layer from AN/gNB towards the PSA UPF, optionally through I-UPFs and in that case N9 interface is used between I-UPF and PSA UPF. Traditionally, UPFs are deployed at central locations and the N3/N9 tunnels extend the PDU layer to them. The N3/N9 interface uses GTP-U tunnels that are typically over a VPN over a transport infrastructure. While N6 is a 3GPP defined interface, it is for reference only and there is no tunneling or specification involved - it is simply a direct IP (in case of IP PDU session) or Ethernet (in case of Ethernet PDU session) connection to the DN.

At the AN/gNB, relay is done between the radio layer and the GTP-U layer. At the PSA UPF, routing/switching is done for IP/Ethernet before GTP-U encapsulation (for downlink traffic) or after GTP-U decapsulation (for uplink traffic).

2. MUP Evolution in 5G: Distributed UPFs

With MEC, ULCL UPFs are deployed closer to gNBs, while centralized PSA UPFs are still used to provide persistent IP addresses to UEs.

In fact, even PSA UPFs could be distributed closer to gNBs and then the N3 interface becomes very simple - over a direct or short transport connection between gNB and UPF (or even an internal connection if the gNB and UPF are hosted on the same server). On the other hand, since the UPF to DN connection is direct, the DN becomes a VPN (e.g., IP VPN in case of IP PDU sessions or EVPN in case of Ethernet PDU sessions) over a transport infrastructure, most likely the same transport infrastructure for the VPN supporting the N3/N9 tunneling in centralized PSA UPF case, as shown in the following picture:

```
                             N3             N6
       UE1         AN1/gNB1   |  PSA UPF1    |
   +---------+                |              |
   |App Layer|                |    routing   |
   +---------+                |+--/---+---\-+|
   |PDU Layer|      relay    || PDU  |     ||       PE1
   +---------+ +---/--+--\---+|+------+IP+L2||    +----+--+
   |         | |      |GTP-U ||GTP-U |     ||----+VRF1|  |
   | 5G-AN   | |5G-AN +------+||------+  or ||    +----+  |
   |         | |      |UDP+IP||UDP+IP|     ||    |VRFn|  |
   | Proto   | |Proto +------+||------+Ether||    +----+--+
   |         | |      |  L2  ||  L2  |     ||   (         )
   | Layers  | |Layers+------+||------+-----+|  (           )
   |         | |      |  L1  ||  L1  |  L1 ||  ( Transport  )
   +---------+ +------+------+|+------+-----+|  (            )
                              |              |  ( Network    )  PE3
                              |              |  (            +--+----+
       UE2         AN2/gNB2   |  PSA UPF2    |  (            |  |VRF1|
   +---------+                |              |  (            |  |----+
   |App Layer|                |    routing   |  (            |  |VRFn|
   +---------+                |+--/---+---\-+|  (            +--+----+
   |PDU Layer|      relay    || PDU  |     ||  (            )
   +---------+ +---/--+--\---+|+------+IP+L2||  (           )
   |         | |      |GTP-U ||GTP-U |     ||   (         )
   | 5G-AN   | |5G-AN +------+||------+  or ||    +----+--+
   |         | |      |UDP+IP||UDP+IP|     ||----+VRF1|  |
   | Proto   | |Proto +------+||------+Ether||    +----+  |
   |         | |      |  L2  ||  L2  |     ||    |VRFn|  |
   | Layers  | |Layers+------+||------+-----+|    +----+--+
   |         | |      |  L1  ||  L1  |  L1 ||      PE2
   +---------+ +------+------+|+------+-----+|
                              |              |
```

The central PSA UPF is no longer needed in this case. Distributed UPF1/UPF2 connect to VRF1 on PE1/PE2 and VRF1 is for the VPN of the DN that UE1/UE2 access. There is also a PE3 for other sites of the VPN, which could be wireline sites including sites providing Internet access.

UEs may keep their persistent IP addresses even when they re-anchor from one PSA UPF to another. In that case, for downlink traffic to be sent to the right UPF, when a UE anchors at a UPF the UPF advertises a host route for the UE and when a UE de-achors from a UPF the UPF withdraws the host route.

While this relies on host routes to direct to-UE traffic to the right UPF, it does not introduce additional scaling burden compared to centralized PSA UPF model, as the centralized UPFs need to maintain per-UE forwarding state (in the form of PDRs/FARs) and the number is the same as the number of host routes that a hub DN router (e.g. vrf1 on PE3 for internet access) need to maintain in the distributed PSA UPFs model. Since the host routes may be lighter-weighted than the PDRs/FARs, the total amount of state may be actually smaller in the distributed model.

For UE-UE traffic, the distributed PSA UPFs may maintain host routes that they learn from each other. With that the UE-UE traffic may take direct UPF-UPF path instead of going through a hub router in the DN (equivalent of central UPF). That is important in LAN-type services that require low delay. Alternatively, the distributed UPFs may maintain only a default route pointing to the hub router like PE3 (besides the host routes for locally anchored UEs). That way, they don't need to maintain many host routes though UPF-UPF traffic has to go through the hub router (and that is similar to all traffic going through a central PSA UPF).

Optionally, even the host routes for locally anchored UEs can be omitted in the FIB of local UPF. Traffic among local UEs can be simply routed to the hub router following the default route, who will then send back to local UPF using VPN tunnels (MPLS or SRv6) that are stitched to GTP tunnels for destination UEs.

2.1. Advantages of Distributed PSA UPFs

Distributed PSA UPFs have the following advantages:

* MEC becomes much simpler - no need for centralized PSA UPF plus ULCL UPFs, and no need for special procedures for location based edge server discovery.

* For LAN-type services, UE-UE traffic can be optimized (no need to go through centralized PSA UPFs) when UPFs maintain host routes. It also allows seamless integration of services across wireline/ wireless-connected customer sites.

* N3/N9 tunneling is simplified

In particular, there is now only short/simple N3 tunneling between AN/gNB and local UPFs in proximity. Among the distributed UPFs and other DN sites, versatile IETF/wireline VPN technologies are used instead. For example:

* Any tunneling technology - MPLS, SR-MPLS or SRV6 - with any traffic engineering/differentiation capabilities can be used. Removal of the GTP/UDP header (and IPv4/IPv6 header in case of MPLS data plane) brings additional bandwidth savings in the transport infrastructure.

* Any control plane model for VPN can be used - traditional distributed or newer controller based route advertisement.

In short, the distributed PSA UPFs model achieves "N3/N9/N6 shortcut and central UPF bypass", which is desired by many operators.

Notice that, since UPF has routing functions, depending on the capability of a UPF device, it may even be possible for a UPF device to act as a VPN PE. That can be done in one of the two models:

* The UPF function and VPN PE function are separate but co-hosted on the same device with a logical/internal N6 connection between them.

* The UPF and VPN PE function are integrated and the PDU sessions become VPN PE-CE links.

The second model is especially useful when a UE is multi-homed to different EVPN PEs in case of Ethernet PDU sessions - EVPN's all-active multihoming procedures can be utilized.

2.2. Extent of Distribution and Open-RAN

The UPFs can be distributed as close to the gNB as being co-located with it - either with a direct local link in between or both running as virtual functions on the same compute server.

In the Open-RAN architecture [ORAN-Arch], the gNB function is split into gNB-CU (O-RAN CU or O-CU, for Central Unit) and gNB-DU (O-RAN DU or O-DU, for Distributed Unit). O-CU is the N3 GTP tunnel endpoint and is what gNB refers to in this document.

Thus, the centralization process of the O-CU component can converge with the distribution process of the UPF up to some optimal and convenient location in the network.

2.3. Enablers of Distributed PSA UPFs

To distribute PSA UPFs, if persistent addresses must be used for UEs, the SMF must be able to allocate persistent IP addresses from a central pool even when a UE re-anchors at different PSA UPFs (e.g. due to mobility). If DHCPv4 is used, either the SMF acts as a central DHCP server or it relays DCHP requests to a central DHCP server on the DN.

The distributed PSA UPFs must be able to advertise host routes in the DN. This should not be a problem since a UPF is essentially a router in that it routes traffic between DN and UEs (that are connected via PDU sessions).

Notice that, advertising host routes for persistent IP addresses is no different from advertising MAC addresses in case of Ethernet PDU sessions.

3. MUP Evolution in 5G: Alternative Implementation Options

3.1. GTP vs. SRv6 vs. MPLS tunneling

3GPP specifies that all tunneling (e.g. N3/N9) use GTP, whose encapsulation includes IP header, UDP header and GTP header. The tunnel is between 3GPP NFs (e.g. gNBs and UPFs) over an IP transport, and the IP transport may be a VPN over the multi-service transport infrastructure of an operator.

There have been proposals to replace GTP with SRv6 tunnels for the following benefits:

* Traffic Engineering (TE) and Service Function Chaining (SFC) capability provided by SRv6

* Bandwidth savings because UDP and GTP headers are no longer needed

While 3GPP has not adopted the proposal, and GTP can be transported over SRv6 (as overlay, instead of SRv6 replacing GTP), some operators still prefer to replace GTP with SRv6 "under the hood". That is, while RAN/UPF still use N2/N4 signaling, the actual tunnel are no longer GTP but SRv6 based on GTP parameters signaled by N2/N4. The SRv6 tunnel could be between two NFs, or a GW could be attached to an NF that still use traditional GTP and the GW will convert GTP to/from SRv6. This is specified in [I-D.ietf-dmm-srv6-mobile-uplane].

Similarly, if an operator prefers to use MPLS, a GTP tunnel can also be replaced with an MPLS PW instead of an SRv6 tunnel. Compared with SRv6, it is even more bandwidth efficient (no need for a minimum

40-byte IPv6 header) and SR-MPLS can also provide TE/SFC capabilities. This is specified in [I-D.zzhang-pals-pw-for-ip-udp-payload].

Note that, While only IPv6 can scale to the 5G requirements for the transport infrastructure, it does not mean MPLS can not be used as data plane in the IPv6 network.

3.2. Routing Based UPF

Traditionally, a UPF is implemented to follow 3GPP specifications. Specifically, N4 signaling is used for SMF to instruct a UPF to set up its session state in terms of PDRs/FARs. On N6 side, a UPF receives downlink traffic with destination addresses that are covered by the UPF's address range for its anchored UEs. The packet is matched against the installed PDRs and forwarded according to the associated FARs. On N3 side, a UPF decapsulates GTP+UDP+IP header of uplink traffic and uses the TEID to identify the DN where inner IP routing or Ethernet switching is done.

[I-D.mhkk-dmm-srv6mup-architecture] specifies a new SRv6 based MUP architecture. When it is applied to a 3GPP based mobile architecture:

* BGP signaling from a MUP Controller replaces N4 signaling from SMF. N4 signaling is still used between the MUP Controller and SMF - from SMF's point of view it is just interacting with a traditional UPF as usual.

* A MUP GW becomes a distributed UPF for uplink traffic.

* A MUP PE, which is different from a usually central PSA UPF, becomes a UPF for downlink traffic, in that traffic to each UE is placed into a different tunnel that is stitched to a GTP tunnel for that UE by a MUP GW (no route lookup is needed on the MUP GW for the downlink traffic).

In this approach UE to UE traffic may still optionally go through the central PSA UPF. This is similar to that a hub router may be used in Section 2.

This approach can be viewed as a specific way of implementing/ deploying distributed UPFs discussed in Section 2. It does have the advantage that from SMF's point of view, nothing is different from before - both from N4 signaling and deployment model point of view.

While the above is specific to SRv6, a similar MPLS based approach will be specified separately for operators who prefer MPLS data plane, and it can even be SR-agnostic.

4. Security Considerations

To be provided.

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2 July 2024

Mobile User Plane Evolution
draft-zzhang-dmm-mup-evolution-09

Abstract

This document describes evolution of mobile user plane in 5G, including distributed User Plane Functions (UPFs) and alternative user plane implementations that some vendors/operators are promoting without changing 3GPP architecture/signaling, and further discusses potentially integrating UPF and Access Node (AN) in 6G mobile networks.

This document is not an attempt to do 3GPP work in IETF. Rather, it discusses potential integration of IETF/wireline and 3GPP/wireless technologies - first among parties who are familiar with both areas and friendly with IETF/wireline technologies. If the ideas in this document are deemed reasonable, feasible and desired among these parties, they can then be brought to 3GPP for further discussions.

Status of This Memo

This Internet-Draft will expire on 3 January 2025.

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1. Current User Plane in 5G

Mobile User Plane (MUP) in 5G [_3GPP-23.501] has two distinct parts: the Access Network part between UE and AN/gNB, and the Core Network part between AN/gNB and UPF.

```
                              N3              N9             N6
       UE           AN(gNB)    |    I-UPF     |  PSA UPF     |
   +---------+                |               |              |
   |App Layer|                |               |    routing   |   __
   +---------+                |               |+--/---+---\-+|   (  )
   |PDU Layer|      relay     |    relay      || PDU  |     ||  (    )
   +---------+ +---/--+--\---+|+---/--+--\---+|+------+IP+L2|| (      )
   |         | |      |GTP-U ||GTP-U |GTP-U ||GTP-U |     || (  DN  )
   | 5G-AN   | |5G-AN +------+|------+------+||------+  or || (      )
   |         | |      |UDP+IP||UDP+IP|UDP+IP||UDP+IP|     ||  (    )
   | Proto   | |Proto +------+||------+------+||------+Ether||   (  )
   |         | |      |  L2  ||  L2  |  L2  ||  L2  |     ||    --
   | Layers  | |Layers+------+||------+------+||------+-----+|
   |         | |      |  L1  ||  L1  |  L1  ||  L1  | L1  ||
   +---------+ +------+------+|+------+------+|+------+-----+|
                              |               |              |
```

For the core network (CN) part, N3 interface extends the PDU layer from AN/gNB towards the PSA UPF, optionally through I-UPFs and in that case N9 interface is used between I-UPF and PSA UPF. Traditionally, UPFs are deployed at central locations and the N3/N9 tunnels extend the PDU layer to them. The N3/N9 interface uses GTP-U tunnels that are typically over a VPN over a transport infrastructure. While N6 is a 3GPP defined interface, it is for reference only and there is no tunneling or specification involved. It is simply a direct IP (in case of IP PDU session) or Ethernet (in case of Ethernet PDU session) connection to the DN.

At the AN/gNB, relay is done between the radio layer and the GTP-U layer. At the PSA UPF, routing/switching is done for IP/Ethernet before GTP-U encapsulation (for downlink traffic) or after GTP-U decapsulation (for uplink traffic).

2. MUP Evolution in 5G

2.1. Distributed UPFs

With MEC, ULCL UPFs are deployed closer to gNBs, while centralized PSA UPFs are still used to provide persistent IP addresses to UEs.

In fact, even PSA UPFs could be distributed closer to gNBs and then the N3 interface becomes very simple â\200\223 over a direct or short transport connection between gNB and UPF (or even an internal connection if the gNB and UPF are hosted on the same server). On the other hand, since the UPF to DN connection is direct, the DN becomes a VPN (e.g., IP VPN in case of IP PDU sessions or EVPN in case of Ethernet PDU sessions) over a transport infrastructure, most likely the same transport infrastructure for the VPN supporting the N3/N9 tunneling in centralized PSA UPF case, as shown in the following picture:

```
                             N3             N6
       UE1         AN1/gNB1   |  PSA UPF1    |
   +---------+                |              |
   |App Layer|                |    routing   |
   +---------+                |+--/---+---\-+|
   |PDU Layer|      relay     || PDU  |     ||      PE1
   +---------+ +---/--+--\---+|+------+IP+L2||    +----+--+
   |         | |      |GTP-U ||GTP-U |     ||----+VRF1|  |
   | 5G-AN   | |5G-AN +------+||------+  or ||    +----+  |
   |         | |      |UDP+IP||UDP+IP|     ||    |VRFn|  |
   | Proto   | |Proto +------+||------+Ether||    +----+--+
   |         | |      |  L2  ||  L2  |     ||   (         )
   | Layers  | |Layers+------+||------+-----+|  (           )
   |         | |      |  L1  ||  L1  |  L1 ||  ( Transport  )
   +---------+ +------+------+|+------+-----+|  (            )
                              |              |  ( Network    )  PE3
                              |              |  (            +--+----+
       UE2         AN2/gNB2   |  PSA UPF2    |  (            |  |VRF1|
   +---------+                |              |  (            |  |----+
   |App Layer|                |    routing   |  (            |  |VRFn|
   +---------+                |+--/---+---\-+|  (            +--+----+
   |PDU Layer|      relay     || PDU  |     ||  (            )
   +---------+ +---/--+--\---+|+------+IP+L2||  (           )
   |         | |      |GTP-U ||GTP-U |     ||   (         )
   | 5G-AN   | |5G-AN +------+||------+  or ||    +----+--+
   |         | |      |UDP+IP||UDP+IP|     ||----+VRF1|  |
   | Proto   | |Proto +------+||------+Ether||    +----+  |
   |         | |      |  L2  ||  L2  |     ||    |VRFn|  |
   | Layers  | |Layers+------+||------+-----+|    +----+--+
   |         | |      |  L1  ||  L1  |  L1 ||      PE2
   +---------+ +------+------+|+------+-----+|
                              |              |
```

The central PSA UPF is no longer needed in this case. Distributed UPF1/UPF2 connect to VRF1 on PE1/PE2 and VRF1 is for the VPN of the DN that UE1/UE2 access. There is also a PE3 for other sites of the VPN, which could be wireline sites including sites providing Internet access.

UEs may keep their persistent IP addresses even when they re-anchor from one PSA UPF to another. In that case, for downlink traffic to be sent to the right UPF, when a UE anchors at a UPF the UPF advertises a host route for the UE and when a UE de-achors from a UPF the UPF withdraws the host route.

While this relies on host routes to direct to-UE traffic to the right UPF, it does not introduce additional scaling burden compared to centralized PSA UPF model, as the centralized UPFs need to maintain per-UE forwarding state (in the form of PDRs/FARs) and the number is the same as the number of host routes that a hub DN router (e.g. vrf1 on PE3 for internet access) need to maintain in the distributed PSA UPFs model. Since the host routes may be lighter-weighted than the PDRs/FARs, the total amount of state may be actually smaller in the distributed model.

For UE-UE traffic, the distributed PSA UPFs may maintain host routes that they learn from each other. With that the UE-UE traffic may take direct UPF-UPF path instead of going through a hub router in the DN (equivalent of central UPF). That is important in LAN-type services that require low delay. Alternatively, the distributed UPFs may maintain only a default route pointing to the hub router like PE3 (besides the host routes for locally anchored UEs). That way, they don't need to maintain many host routes though UPF-UPF traffic has to go through the hub router (and that is similar to all traffic going through a central PSA UPF).

Optionally, even the host routes for locally anchored UEs can be omitted in the FIB of local UPF. Traffic among local UEs can be simply routed to the hub router following the default route, who will then send back to local UPF using VPN tunnels (MPLS or SRv6) that are stitched to GTP tunnels for destination UEs.

2.1.1. Advantages of Distributed PSA UPFs

Distributed PSA UPFs have the following advantages:

* MEC becomes much simpler - no need for centralized PSA UPF plus ULCL UPFs, and no need for special procedures for location based edge server discovery.

* For LAN-type services, UE-UE traffic can be optimized (no need to go through centralized PSA UPFs) when UPFs maintain host routes. It also allows seamless integration of services across wireline/ wireless-connected customer sites.

* N3/N9 tunneling is simplified

In particular, there is now only short/simple N3 tunneling between AN/gNB and local UPFs in proximity. Among the distributed UPFs and other DN sites, versatile IETF/wireline VPN technologies are used instead. For example:

* Any tunneling technology - MPLS, SR-MPLS or SRV6 - with any traffic engineering/differentiation capabilities can be used. Removal of the GTP/UDP header (and IPv4/IPv6 header in case of MPLS data plane) brings additional bandwidth savings in the transport infrastructure.

* Any control plane model for VPN can be used - traditional distributed or newer controller based route advertisement.

In short, the distributed PSA UPFs model achieves "N3/N9/N6 shortcut and central UPF bypass", which is desired by many operators.

Notice that, since UPF has routing functions, depending on the capability of a UPF device, it may even be possible for a UPF device to act as a VPN PE. That can be done in one of the two models:

* The UPF function and VPN PE function are separate but co-hosted on the same device with a logical/internal N6 connection between them.

* The UPF and VPN PE function are integrated and the PDU sessions become VPN PE-CE links.

The second model is especially useful when a UE is multi-homed to different EVPN PEs in case of Ethernet PDU sessions - EVPN’s all-active multihoming procedures can be utilized.

2.1.2. Enablers of Distributed PSA UPFs

To distribute PSA UPFs, if persistent addresses must be used for UEs, the SMF must be able to allocate persistent IP addresses from a central pool even when a UE re-anchors at different PSA UPFs (e.g. due to mobility). If DHCPv4 is used, either the SMF acts as a central DHCP server or it relays DCHP requests to a central DHCP server on the DN.

The distributed PSA UPFs must be able to advertise host routes in the DN. This should not be a problem since a UPF is essentially a router in that it routes traffic between DN and UEs (that are connected via PDU sessions).

Notice that, advertising host routes for persistent IP addresses is no different from advertising MAC addresses in case of Ethernet PDU sessions.

2.2. Alternative Transport Options for 5G

2.2.1. GTP vs. SRv6 vs. MPLS tunneling

3GPP specifies that all tunneling (e.g. N3/N9) use GTP, whose encapsulation includes IP header, UDP header and GTP header. The tunnel is between 3GPP NFs (e.g. gNBs and UPFs) over an IP transport, and the IP transport may be a VPN over the multi-service transport infrastructure of an operator.

There have been proposals to replace GTP with SRv6 tunnels for the following benefits:

* Traffic Engineering (TE) and Service Function Chaining (SFC) capability provided by SRv6

* Bandwidth savings because UDP and GTP headers are no longer needed

While 3GPP has not adopted the proposal, and GTP can be transported over SRv6 (as overlay, instead of SRv6 replacing GTP), some operators still prefer to replace GTP with SRv6 "under the hood". That is, while RAN/UPF still use N2/N4 signaling, the actual tunnel are no longer GTP but SRv6 based on GTP parameters signaled by N2/N4. The SRv6 tunnel could be between two NFs, or a GW could be attached to an NF that still use traditional GTP and the GW will convert GTP to/from SRv6. This is specified in [I-D.ietf-dmm-srv6-mobile-uplane].

Similarly, if an operator prefers to use MPLS, a GTP tunnel can also be replaced with an MPLS PW instead of an SRv6 tunnel. Compared with SRv6, it is even more bandwidth efficient (no need for a minimum 40-byte IPv6 header) and SR-MPLS can also provide TE/SFC capabilities. This is specified in [I-D.zzhang-pals-pw-for-ip-udp-payload].

Note that, While only IPv6 can scale to the 5G requirements for the transport infrastructure, it does not mean MPLS can not be used as data plane in the IPv6 network.

2.2.2. Routing Based UPF-Lite

Traditionally, a UPF is implemented to follow 3GPP specifications. Specifically, N4 signaling is used for SMF to instruct a UPF to set up its session state in terms of PDRs/FARs. On N6 side, a UPF receives downlink traffic with destination addresses that are covered by the UPF’s address range for its anchored UEs. The packet is matched against the installed PDRs and forwarded according to the associated FARs. On N3 side, a UPF decapsulates GTP+UDP+IP header of uplink traffic and uses the TEID to identify the DN where inner IP routing or Ethernet switching is done.

[I-D.mhkk-dmm-srv6mup-architecture] specifies a new SRv6 based MUP architecture. When it is applied to a 3GPP based mobile architecture:

* BGP signaling from a MUP Controller replaces N4 signaling from SMF. N4 signaling is still used between the MUP Controller and SMF - from SMF's point of view it is just interacting with a traditional UPF as usual.

* A MUP GW becomes a distributed UPF for uplink traffic.

* A MUP PE, which is different from a usually central PSA UPF, becomes a UPF for downlink traffic, in that traffic to each UE is placed into a different tunnel that is stitched to a GTP tunnel for that UE by a MUP GW (no route lookup is needed on the MUP GW for the downlink traffic).

In this approach UE to UE traffic may still optionally go through the central PSA UPF. This is similar to that a hub router may be used in Section 2.1.

This approach can be viewed as a specific way of implementing/ deploying a subset of functionalities of distributed UPFs discussed in Section 2.1, specifically the routing/switching functionalities, hence often referred to as UPF-Lite. It does have the advantage that from SMF's point of view, nothing is different from before - both from N4 signaling and deployment model point of view.

While the above is specific to SRv6, a similar MPLS based approach will be specified separately for operators who prefer MPLS data plane, and it can even be SR-agnostic.

3. MUP Evolution for 6G

This section discusses potential MUP evolution in 6G mobile networks. It does involve changes in 3GPP architecture and signaling, so the purpose is to share the ideas in IETF/wireline community first. If it gains consensus within IETF/wireline community especially among mobile operators, then the proposal may be brought to 3GPP community for further discussions.

3.1. UPF Distribution and RAN Decomposition

As described earlier, with 5G, in the opposite direction of UPF distribution, some RAN components are becoming centralized as a result of the disaggregation and decomposition of baseband processing functions. The AN functionality is now divided into the Radio Unit (RU, comprising the antenna and radiating elements), the Distributed Unit (DU, comprising the functions for the real time processing of the signal), and the Centralized Unit (CU, comprising the remaining signal processing functions). CU is the AN function that handles N3 GTP-U encapsulation for UpLink (UL) traffic and decapsulation for DownLink (DL) traffic.

The placement of the decomposed CU component can converge with the distribution process of the UPF to some optimal and convenient location in the network - they become co-located in an edge or far edge data center (DC) either with direct/short local connections in between or both running as virtual functions on the same compute server.

3.2. Integrated AN/UP Function (ANUP)

While the AN (CU) and UPF can be co-located, in 5G they are still separate functions connected by N3 tunneling over a short/internal transport connection. Routing happens on the UPF between the DN and UEs over the N3 tunnels, and relay happens on the AN between the N3 tunnels and AN protocol stack.

With AN and UPF functions more and more disaggregated and virtualized even in 5G, it is becoming more and more feasible and attractive to integrate the AN and UPF functions, eliminating the N3 tunneling and the relay on AN entirely. The combined function is referred to as ANUP in this document, which does routing between DN and UEs over the AN protocol stack directly:

```
                            N6
       UE1          ANUP     |
   +---------+               |
   |App Layer|     routing   |
   +---------+ +--/---+---\-+|
   |PDU Layer| | PDU  |     ||      PE1
   +---------+ +------+IP+L2||    +----+--+
   |         | |      |     ||----+VRF1|  |
   | xG-AN   | |xG-AN +  or ||    +----+  |
   |         | |      |     ||    |VRFn|  |
   | Proto   | |Proto +Ether||    +----+--+
   |         | |      |     ||   (         )
   | Layers  | |Layers+-----+|  (           )
   |         | |      |  L1 ||  ( Transport  )
   +---------+ +------+-----+|  (            )
                             |  ( Network    )  PE3
                             |  (            +--+----+
       UE2          ANUP     |  (            |  |VRF1|
   +---------+               |  (            |  |----+
   |App Layer|     routing   |  (            |  |VRFn|
   +---------+ +--/---+---\-+|  (            +--+----+
   |PDU Layer| | PDU  |     ||  (            )
   +---------+ +------+IP+L2||  (           )
   |         | |      |     ||   (         )
   | xG-AN   | |xG-AN +  or ||    +----+--+
   |         | |      |     ||----+VRF1|  |
   | Proto   | |Proto +Ether||    +----+  |
   |         | |      |     ||    |VRFn|  |
   | Layers  | |Layers+-----+|    +----+--+
   |         | |      |  L1 ||      PE2
   +---------+ +------+-----+|
                             |
```

With this architecture, 3GPP and IETF technologies are applied where they are best applicable: 3GPP technologies responsible for radio access and IETF technologies for the rest. As IETF technologies continue to evolve, they can be automatically applied in mobile networks without any changes in 3GPP architecture/specification.

One way to view this is that the ANUP is a router/switch with wireless and wired interfaces and it routes/switches traffic among those interfaces. The wireless interface is established by 3GPP technologies (just like an Ethernet interface is established by IEEE technologies) and the routing/switching function follows IETF/IEEE standards.

Some advantages of this new architecture include:

* 5G-LAN and MEC become transparent applications that wireline networks have been supporting (PDU sessions terminate into the closest ANUP and routed/switched to various DNs).

* MBS becomes very simple â\200\223 the ANUP gets the multicast traffic in the DN and then use either shared radio bearer or individual bearers to send to interested UEs.

* Simplified signaling - instead of seven-steps of separate N2/N4 signaling from separate AMF/SMF to separate AN/UPF and N11 signaling between AMF and SMF to set up the N3 tunneling for a PDU session, a two-step signaling between a new single control plane entity to the single integrated ANUP is enough - see Section 4.2 for details.

* Simplified/Optimized data plane - AN-UPF connection and GTP-U encapsulation/decapsulation are not needed anymore. This can significantly improve throughput, especially when compared to AN/UPF functions running on servers.

* Natural local break-out in traffic forwarding, by allowing the more efficient routing/switching of traffic according to its destination.

* Any kind of tunnels can be used for the DN VPN, whether it is MPLS or SRv6, w/o the overhead of UDP/GTP encapsulation compared to GTP tunneling. Network slicing and QoS functions are still supported (even with current GTP tunneling the transport network need to instantiate slices and implement QoS for N3/N9 tunnels as well).

Because the ANUP already implement the routing/switching functions, even the PE functions (for the DN VPN) could be optionally integrated into it, further streamlining end-to-end communication by reducing NFs and connections between them. While integrating PE function is optional, it is desired and today’s AN can be already considered as a PE (Section 4.6).

3.3. ANUP Potential Use-case: 5G-A Satellite Services

The 3GPP SA2 working group has several projects to study & standardize the 5G advanced services whose wireless connectivities are provided via satellite networks. These projects cover various aspects of satellite services, e.g., one focusing on the support of wireless access considering the satellite-based discontinuous coverage, while the 2nd-one studying the service requirements via satellite backhaul taking into account 5G new capabilities.

Still, there is a 3rd project exploring the scenario that a gNB will be on board satellite while the corresponding anchor UPF may (i.e., on-board a satellite) or may not (i.e., on the ground). Evidently, this is a very challenging case that requires the seamless integration among AN (i.e., gNB), UPF & 5GS.

An on-board UPF might not share the same underlaying satellite as the matching gNB. For this case, thanks to the everlasting movement of (LEO-based) satellites, the highly mobile satellite constellation network will significantly impact the signaling performance between the gNB and the UPF. Therefore, some measures must be adopted to reduce the signalling impact to the AN/RAT, to the UP (UPF) and to the CP (5GS).

Further, a latest 5G-service, the satellite-based store & foward (S&F) feature for (on-ground) UEs via intermittent (satellite) service-link and/or feed-link connectivities [_3GPP-23.700-29], has embraced quite a few proposals in which the AN (i.e. gNB), the CP (i.e., 5GS/EPC) and the UP (i.e., UPF/S-GW,P-GW) could be either deployed together (being less challenging) or distributed (being much more complicated). In some proposal(s), even an individual CP and/or UP NF (network function) might be decomposed into multiple (sub)-instances to accomodate the complexity of distributedness. However, if we plug into the above S&F service requirements into the integrated ANUP architecture, there is no more implication of the distribution of gNB and UPF. The complexity of both the CP signaling exchanges and the UP data transport will be greatly relieved.

Given the ubiquitous discussion of the satellite communication for 5G, beyond-5G and imminent 6G, we do believe our proposal ANUP will benefit materially both the IETF and the 3GPP communities.

3.4. ANUP-like Feature in 4G: Local IP Access (LIPA)

While Section 3.2 proposed the integrated AN and UPF, or ANUP, for the evolution of 6G MUP, the 3GPP specification 23.401 [_3GPP-23.401] has already standardized an ANUP-like function, i.e., the Local IP Access or LIPA, that fundamentally integrates together the 4G RAN entity 'HeNB or Home eNodeB' and the traffic switching gateway 'L-GW or Local Gateway'.

```
        LIPA @ DN            DN: Data Network
       ^     |               UP: User Plane
       |     |SGi
       |  +--+---+    S5
       |  | L-GW |-----------\
       |  +------+   S1-U     \+-----+  S5  +------+ SGi  /----\
       |  | HeNB +-------------+ SGW +------+ P-GW +-----<  DN  >
       |  +--+---+\            +-----+      +------+      \----/
     UP|     |     \S1-MME    /S11
       |     |Uu    \        /
       |  +-----+    +------+
       |  |     |    |  MME |
       +--+ UE  |    +------+
          +-----+
```

The above figure shows the LIPA architecture. It enables a UE (on the bottom-left) that can connect via a HeNB to access the DN without the user plane traversing the mobile operator’s network (e.g., SGW->P-GW). The LIPA feature is achieved using a L-GW (on the top-left) that is collocated with the HeNB. The functionalities of HeNB and L-GW are integrated together to provide the direct User-Plane (UP) path between the HeNB and the L-GW. There is NO reference interface between HeNB and L-GW. That is, they are truly an integrated entity.

As of now, while the LIPA feature has not yet been deployed extensively by MNO’s, it does give somewhat promising indicator that the ANUP-like integration solution has been studied before by 3GPP and it is worthy of the continuous exploration.

4. ANUP: Advanced Technical Considerations

Various considerations/concerns were brought up during the discussions of the ANUP proposal. They are documented in the following sections.

4.1. Separate AN/UP Functions

There are still cases where separate AN/UP functions are desired/ required:

* An MNO may want to deploy one UPF for a cluster of ANs in proximity in some scenarios/locations

* An MNO may support MVNOs who have their own UP functions but make use of the hosting MNO’s ANs

* Home Routed roaming requires separate HPLMN UPs and VPLMN ANs

Therefore, the integration does not have to be always used. Rather, it is "integration when desired and feasible, separation when necessary".

Note that, the same ANUP can handle both situations - some PDU sessions may be tunneled to a separate UPF while other sessions are terminated and then traffic is routed/switched to either local DN or remote/central DN.

This is also the basis of interworking between 5G and xG:

* A 5G AN can have N3 tunneling to an xG UPF

* An xG ANUP can have N3 tunneling to a 5G/xG UPF

4.2. Simplified/reduced Signaling and optimized data plane

One may ask why bother with integration when it is still needed to support separate AN and UPF anyway.

When AN and UPF are separate, to set up the N3 tunnel the following seven steps are needed, involving four NFs and three Nx interfaces:

1. SMF sends request to UPF (N4)

2. UPF responds with UPF-TEID (N4)

3. SMF passes <UPF, UPF-TEID> to AMF (N11)

4. AMF sends request to gNB, passing <UPF, UPF-TEID> (N2)

5. gNB responds with AN-TEID (N2)

6. AMF passes <AN, AN-TEID> to SMF (N11)

7. SMF sends <AN, AN-TEID> to UPF (N4)

With integrated ANUP, there is no need for N3 tunnel anymore. A new control plane NF only needs to tell the ANUP which DN that PDU session belongs to.

Additionally, the N3 tunnel is maintained by periodical signaling refreshes - otherwise timeout will happen. This causes significant control plane load on the NFs and interfaces, which no longer exists with ANUP since N3 tunneling is eliminated.

As mentioned before, with ANUP the AN-UPF connection and GTP-U encapsulation/decapsulation are not needed anymore. This can significantly improve performance/throughput, especially when compared to AN/UPF functions running on servers.

4.3. Microservice architecture

One may argue that the integration of AN and UP functions are against the microservice trend.

The following is a verbatim quote from https://microservices.io/:

> Microservices - also known as the microservice architecture - is an architectural style that structures an application as a collection of services that are:
>
> - Highly maintainable and testable
> - Loosely coupled
> - Independently deployable
> - Organized around business capabilities
> - Owned by a small team
> - The microservice architecture enables the rapid, frequent and reliable delivery of large, complex applications. It also enables an organization to evolve its technology stack.

The counter argument is that microservice is about decomposing complex "applications". ANUP is about integrating co-located and mature data plane entities to streamline and optimize forwarding. It has real and significant benefits of simplified signaling and optimized data plane - it does not make sense to force microservice here for data plane. Note that microservices can still be utilized in the control plane for ANUP.

4.4. Increased burden on previously simple AN

One may think that the AN only needed to do simple traffic stitching functions while now the ANUP has added UPF burden. However, the main use case of ANUP is where the AN and UPF are co-located even if they are separate functions. Therefore, the ANUP only absorbs the whatever functionalities that the separate UPF at the same site need to do anyway, with reduced signaling and data plane handling - the overall processing at the site actually decreases. While a particular ANUP now has more processing to do, it can offload some sessions to additional ANUPs that are now made possible because of removal of separate UPFs at the same site.

This may also make it easier to allocate resources at the edge DC. Previously, an operator needs to consider how much resources to allocate for the separate UPFs and assign which sessions to which UPFs. Now it simply is to decide which sessions are assigned to which ANUP (just like to decide which sessions are assigned to which AN).

In addition, there are some similar or even overlapping functionalities in the current UPF and AN in 5GS; in integrated ANUP these functions can be re-designed. For example for a rate control enforcement, UPF supports the enforcement of the aggregated MBR for the session (Session-AMBR) in UL/DL directions, while AN can enforce the aggregated MBR for the UE (UE-AMBR) in UL/DL directions. Both UPF and AN support the enforcement of the QoS Flow MBR (MFBR) and GBR (GFBR) in both UL/DL directions (for the GBR flows), while AN can in additon to ensure the UE-Slice-MBR is not exceeded in UL/DL directions. With ANUP, these previously separate functions may be optimized now that they are in the same entity.

4.5. Use of ULCL I-UPF for MEC Purpose

Notice that the ANUP is to integrate AN and distributed UPF that are co-located in edge DCs, and one use case of distributed UPF (in those edge DCs) is MEC. UpLink CLassifier Intermediate UPF (ULCL I-UPF) is an existing way to achieve local breakout routing for MEC purpose, but it is not an optimized/elegant solution compared to ANUP.

The ULCL I-UPF is placed between an AN and a central UPF as a filtering device. While called an UPF it is different from a typical UPF - It inspects _all_ GTP-U UL traffic, and based on N4 signaling from SMF certain traffic is intercepted and forwarded to local DN. This places additional control plane burden on SMF in addition to the need of the special traffic-filtering UPF. For example, the SMF will need to know which traffic (to some particular destination address) is to be intercepted.

For comparison, with ANUP there is no need for the additional special UPF and corresponding N4 signaling at all. Everything is standard routing/filtering w/o relying on SMF to determine which traffic is delivered locally:

* For some PDU sessions, all traffic may be tunneled to a separate UPF.

* For a particular PDU session, some traffic may be delivered locally while some other delivered to the central/remote DN all based on routing/filtering in the DN.

4.6. VPN PE Function in AN/ANUP

As previously mentioned, the ANUP can optionally have the VPN PE function integrated, instead of being a standalone CE device for the VPN for the DN.

While optional, it is a desired optimization. Moreover, even the separate AN itself can be considered as a spoke PE for a hub-and-spoke VPN [RFC7024] for the DN.

Consider a hub-and-spoke VPN outside the mobile network context:

* A spoke PE only imports a default route from a hub PE and therefore sends all traffic from its CEs to the hub PE

* A hub PE imports routes from all PEs and sends traffic to appropriate PEs or its CEs, whether the traffic is from a local CE or another PE

Additionally, consider that a spoke PE advertise different per-prefix (vs. per VRF) VPN labels. When it receives traffic with a per-prefix label, it can send traffic to a local CE purely based on the label without having to do a route lookup in the VRF.

Now consider the AN and the central UPF in a mobile network. Effectively the AN is a spoke PE and the central UPF is a hub PE for the DN:

* The GTP-U tunnel corresponds to the MPLS label stack.

* For UL traffic, there is no need for route lookup on the AN because all is to be tunneled to the UPF. The UPF TEID is used by the UPF to determine which DN the traffic belongs to, just like how a VPN label is used to determine VPN the traffic belongs to.

* For DL traffic, the UPF does a lookup based on the destination address (e.g., that of a UE) and a corresponding GTP-U tunnel is used to send traffic to an AN. When traffic arrives on the AN, the per-UE TEID allows traffic to be relayed to the UE without a route lookup.

In other words, the separate ANs and UPF form a hub-and-spoke VPN for the DN with per-prefix "labels", though no VRF is present on the ANs because there is no need for route lookup at all.

For ANUP with VPN PE function integrated, the only difference is the addition of VRF in the AN. That’s so that some sessions will be locally terminated and traffic is locally routed. For DL traffic, the ANUP can either advertise per-VRF label (or SID in case of SR) and do a lookup for DL traffic, or advertises per-prefix/UE label (or SID in case of SR) - just like per-UE TEID - so that it does not to do a lookup before sending traffic to a UE.

4.7. QoS Handling

With separate AN and UPF, the QoS handling happens in the following segments:

* Between UE and AN over the air interface

* Between AN and UPF over the N3 tunnel, which can be:

  - through a transport network, or

  - through a local/internal link in co-location case

The QoS over the air interface is the same for both AN and ANUP cases.

For the trivial QoS previously over N3 tunnel through a local/internal link in co-location case, it is now completely eliminated with ANUP.

The QoS over N3 tunnel through a transport network is realized through QoS mechanisms in the transport network. With ANUP, it's likely that similar QoS is needed between the ANUP and a hub router in the DN, which is a VPN over the same transport network. Therefore, it is similar to the QoS over N3 tunnel - only that now it is QoS over VPN tunnel and realized through QoS mechanisms in the transport network.

A central UPF may have rate limiting for N3 tunnels so that each PDU session's DL traffic is limited and the AN won't be overwhelmed by DL traffic. With distributed UPF (whether integrated into AN or not), the routes advertised to the hub DN router may carry QoS information like rate limiting parameters, so that the hub DN router can do rate limiting.

4.8. NAT

Addresses assigned to UEs may be from a private address space and NAT is needed between the private space and public space. In case of central UPFs, the NAT can be done on a central UPF (though NAT is still a logically separate function) or by a separate NAT Gateway (GW) connected to the central UPF.

With distributed UPFs (whether it is a separate UPF or an integrated ANUP), NAT can be done by a central NAT GW connected to the hub router, just like a NAT GW on or next to the previously central UPF.

A large operator may have multiple central UPFs for different regions, and the regions may have overlapping private address spaces. Each UPF will have its own NAT GW, and UE to UE traffic across regions will go throw two NAT GWs. With distributed UPFs, each region will have its own hub router with its own NAT GW, and UE to UE traffic across regions will go through two NAT GWs and two hub routers.

5. ANUP Implications: IETF to 3GPP

5.1. User-plane/UP vs. Control-plane/CP

Stepping from the IETF perspective, this draft centers around the ANUP innovations along with its implications to 3GPP SDO. Because IETF focuses more on the connectivity of transport network (TN), this draft addresses mainly the mobile user plane or UP, e.g., re-design of the hub-and-spoke VPN settings different from those over the current separate AN & UPF architecture, alternative UP protocol(s) to GTP-U tunnel between AN and UPF (in the TN domain), etc. However, while this draft does not limit the discussions only to UP, but given the complexities of the 5G CP and the on-going discussions of the evolution of the 6G system architecture, the draft does not dive into the CP of the mobile wireless domain. All those mobility related CP details, e.g., RM, MM, SM, paging, handover, QoS settings, etc., are left to the 3GPP’s further exploration & refinement. Certainly, the results from the UP investigation would benefit the CP design in 6G evolution.

5.2. Impacts & Intentions to 5G/6G CP

As set forth at the beginning, this draft does not intend to do the 3GPP 5G/6G work in IETF. In comparison, it actually acknowledges the principle that the complete studies should be done in the 3GPP SDO. The I.D. has argued that the innovative ANUP architecture does have certain advantageous impacts to the current 5GS CP (and likely to the future 6G evolution). But, given the complexity of 5GS, any ANUP related achievement in the IETF domain shall only serve as a reference to the 3GPP, possibly via the liaison exchange between the two SDO’s.

6. Security Considerations

To be provided.

7. Acknowledgements

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