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Transmission of IPv6 Packets over Aeronautical ("aero") Interfaces
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Abstract

Aeronautical mobile nodes (e.g., aircraft of various configurations) communicate with networked correspondents over multiple access network data links and configure mobile routers to connect their on-board networks. An Air-to-Ground (A/G) interface specification is therefore needed for coordination with the ground domain network. This document specifies the transmission of IPv6 packets over aeronautical ("aero") interfaces.

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1. Introduction

Aeronautical Mobile Nodes (MNs) such as aircraft of various configurations often have multiple data links for communicating with networked correspondents. These data links may have differing performance, cost and availability characteristics that can change dynamically according to mobility patterns, flight phases, proximity to infrastructure, etc.

Each MN receives an IPv6 Mobile Network Prefix (MNP) that can be used by on-board networks independently of the access network data links selected for data transport. The MN performs router discovery (i.e., similar to IPv6 customer edge routers [RFC7084]) and acts as a mobile router on behalf of its on-board networks.

The MN configures a virtual interface (termed the "aero interface") as a thin layer over the underlying access network interfaces. The aero interface is therefore the only interface abstraction exposed to the IPv6 layer and behaves according to the Non-Broadcast, Multiple Access (NBMA) interface principle, while underlying access network interfaces appear as link layer communication channels in the architecture. The aero interface connects to a virtual overlay cloud service known as the "aero link". The aero link spans a worldwide Internetwork that may be either a private-use infrastructure or the global public Internet itself.

The aero interface provides a traffic engineering nexus for guiding inbound and outbound traffic to the correct underlying Access Network (ANET) interface(s). The IPv6 layer sees the aero interface as a point of connection to the aero link. Each aero link has one or more associated Mobility Service Prefixes (MSPs) from which aero link MNPs are derived. If there are multiple aero links, the IPv6 layer will see multiple aero interfaces.

The aero interface interacts with the ground-domain Mobility Service (MS) through IPv6 Neighbor Discovery (ND) control message exchanges [RFC4861]. The MS provides Mobility Service Endpoints (MSEs) that track MN movements and represent their MNPs in a global routing or mapping system.

This document specifies the transmission of IPv6 packets [RFC8200] and MN/MS control messaging over aeronautical ("aero") interfaces.

2. Terminology

The terminology in the normative references applies; especially, the terms "link" and "interface" are the same as defined in the IPv6 [RFC8200] and IPv6 Neighbor Discovery (ND) [RFC4861] specifications.

The following terms are defined within the scope of this document:

Access Network (ANET)
: a data link service network (e.g., an aviation radio access network, satellite service provider network, cellular operator network, etc.) protected by physical and/or link layer security. Each ANET provides an Access Router (AR), and connects to outside Internetworks via border security devices such as proxys, firewalls, packet filtering gateways, etc.

ANET interface
: a node's attachment to a link in an ANET.

Internetwork (INET)

a connected network region with a coherent IP addressing plan that provides transit forwarding services for ANET mobile nodes and INET correspondents. Examples include private enterprise networks, aviation networks and the global public Internet itself.

INET interface
a node's attachment to a link in an INET.

aero link
a virtual overlay cloud service configured over one or more INETs and their connected ANETs. An aero link may comprise multiple INET segments joined by bridges the same as for any link; the addressing plans in each segment may be mutually exclusive and managed by different administrative entities.

aero interface
a node's attachment to an aero link, and configured over one or more underlying ANET/INET interfaces.

aero address
an IPv6 link-local address constructed as specified in Section 7, and assigned to an aero interface.

3. Requirements

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 [RFC2119]. Lower case uses of these words are not to be interpreted as carrying RFC2119 significance.

4. Aeronautical ("aero") Interface Model

An aero interface is a MN virtual interface configured over one or more ANET interfaces, which may be physical (e.g., an aeronautical radio link) or virtual (e.g., an Internet or higher-layer "tunnel"). The MN coordinates with the MS through IPv6 ND message exchanges.

The aero interface architectural layering model is the same as in [RFC7847], and augmented as shown in Figure 1. The IPv6 layer therefore sees the aero interface as a single network layer interface with multiple underlying ANET interfaces that appear as link layer communication channels in the architecture.

```
                                    +----------------------------+
                                    |           TCP/UDP          |
             Session-to-IP    +---->|                            |
             Address Binding  |     +----------------------------+
                              +---->|             IPv6           |
             IP Address       +---->|                            |
             Binding          |     +----------------------------+
                              +---->|       aero Interface       |
             Logical-to-      +---->|       (aero address)       |
             Physical         |     +----------------------------+
             Interface        +---->|  L2  |  L2  |       |  L2  |
             Binding                |(IF#1)|(IF#2)| ..... |(IF#n)|
                                    +------+------+       +------+
                                    |  L1  |  L1  |       |  L1  |
                                    |      |      |       |      |
                                    +------+------+       +------+
```

Figure 1: Aero Interface Architectural Layering Model

The aero virtual interface model gives rise to a number of opportunities:

- o since aero interface link-local addresses are uniquely derived from an MNP (see: Section 7, no Duplicate Address Detection (DAD) messaging is necessary over the aero interface.

- o ANET interfaces can remain unnumbered in environments where communications are coordinated entirely over the aero interface.

- o as ANET interface properties change (e.g., link quality, cost, availability, etc.), any active ANET interface can be used to update the profiles of multiple additional ANET interfaces in a single message. This allows for timely adaptation and service continuity under dynamically changing conditions.

- o coordinating ANET interfaces in this way allows them to be represented in a unified MS profile with provisions for mobility and multilink operations.

- o exposing a single virtual interface abstraction to the IPv6 layer allows for traffic engineering (including QoS based link selection, packet replication, load balancing, etc.) at the link layer while still permitting queuing at the IPv6 layer based on, e.g., traffic class, flow label, etc.

- o the IPv6 layer sees the aero interface as a point of connection to the aero link; if there are multiple aero links (i.e., multiple MS's), the IPv6 layer will see multiple aero interfaces.

Other opportunities are discussed in [RFC7847].

Figure 2 depicts the architectural model for a MN connecting to the MS via multiple independent ANETs. When an ANET interface becomes active, the MN sends native (i.e., unencapsulated) IPv6 ND messages via the underlying ANET interface. IPv6 ND messages traverse the ground domain ANETs until they reach an Access Router (AR#1, AR#2, .., AR#n). The AR then coordinates with a Mobility Service Endpoint (MSE#1, MSE#2, ..., MSE#m) in the INET and returns an IPv6 ND message response to the MN. IPv6 ND messages traverse the ANET at layer 2; hence, the Hop Limit is not decremented.

```
                           +--------------+
                           |      MN      |
                           +--------------+
                           |aero inteface |
                           +----+----+----+
                  +--------|IF#1|IF#2|IF#n|------ +
                 /         +----+----+----+        \
                /                 |                 \
               /         Native   |   IPv6           \
              v                   v                   v
           (:::)-.              (:::)-.              (:::)-.
      .-(::ANET:::)        .-(::ANET:::)        .-(::ANET:::)
        `-(::::)-'           `-(::::)-'           `-(::::)-'
          +----+               +----+               +----+
    ...   |AR#1|  ..........   |AR#2|   .........   |AR#n|  ...
   .      +-|--+               +-|--+               +-|--+     .
   .        |                    |                    |
   .        v                    v                    v        .
   .               <-----  Encapsulation ----->                .
   .                                                           .
   .      +-----+               (:::)-.                        .
   .      |MSE#2|           .-(::::::::)          +-----+      .
   .      +-----+       .-(:::   INET  :::)-.     |MSE#m|      .
   .                  (:::::    Routing  ::::)    +-----+      .
   .                     `-(::: System :::)-'                  .
   .  +-----+                `-(:::::::-'                      .
   .  |MSE#1|          +-----+               +-----+           .
   .  +-----+          |MSE#3|               |MSE#4|           .
   .                   +-----+               +-----+           .
   .                                                           .
   .                                                           .
   .       <----- Worldwide Connected Internetwork ---->       .
    ...........................................................
```

Figure 2: MN/MS Coordination via Multiple ANETs

After the initial IPv6 ND message exchange, the MN can send and receive unencapsulated IPv6 data packets over the aero interface. Traffic engineering will forward the packets via ARs in the correct underlying ANETs. The AR encapsulates the packets according to the capabilities provided by the MS and forwards them to the next hop within the worldwide connected Internetwork via optimal routes.

5. Maximum Transmission Unit

All IPv6 interfaces MUST configure an MTU of at least 1280 bytes [RFC8200]. The aero interface configures its MTU based on the largest MTU among all underlying ANET interfaces. The value may be overridden if an RA message with an MTU option is received.

The aero interface returns internally-generated IPv6 Path MTU Discovery (PMTUD) Packet Too Big (PTB) messages [RFC8201] for packets admitted into the aero interface that are too large for the outbound underlying ANET interface. Similarly, the aero interface performs PMTUD even if the destination appears to be on the same link since a proxy on the path could return a PTB message. PMTUD therefore ensures that the aero interface MTU is adaptive and reflects the current path used for a given data flow.

Applications that cannot tolerate loss due to MTU restrictions should refrain from sending packets larger than 1280 bytes, since dynamic path changes can reduce the path MTU at any time. Applications that may benefit from sending larger packets even though the path MTU may change dynamically can use larger sizes.

6. Frame Format

The aero interface transmits IPv6 packets according to the native frame format of each underlying ANET interface. For example, for Ethernet-compatible interfaces the frame format is specified in [RFC2464], for aeronautical radio interfaces the frame format is specified in standards such as ICAO Doc 9776 (VDL Mode 2 Technical Manual), for tunnels over IPv6 the frame format is specified in [RFC2473], etc.

7. Link-Local Addresses

Aero interfaces assign link-local addresses the same as any IPv6 interface. The link-local address format for aero interfaces is known as the "aero address".

MN aero addresses begin with the prefix fe80::/64 followed by a 64-bit prefix taken from the MNP (see: Appendix B). The lowest-numbered aero address serves as the "base" address. The MN uses the

base aero address in IPv6 ND messages, but accepts packets destined to all aero addresses equally. For example, for the MNP 2001:db8:1000:2000::/56 the corresponding aero addresses are:

fe80::2001:db8:1000:2000

fe80::2001:db8:1000:2001

fe80::2001:db8:1000:2002

... etc. ...

fe80::2001:db8:1000:20ff

MSE aero addresses are allocated from the range fe80::/96, and MUST be managed for uniqueness by the collective aero link administrative authorities. The lower 32 bits of the address includes a unique integer value, e.g., fe80::1, fe80::2, fe80::3, etc. The address fe80:: is the IPv6 link-local Subnet Router Anycast address [RFC4291] and the address fe80::ffff:ffff is reserved; hence, these values are not available for general assignment.

The IPv6 addressing architecture [RFC4291] reserves the prefix ::/8; this assures that MNPs will not begin with ::/32 so that MN and MSE aero addresses cannot overlap.

Since MN aero addresses are based on the distribution of administratively assured unique MNPs, and since MSE aero addresses are guaranteed unique through administrative assignment, aero interfaces set the autoconfiguration variable DupAddrDetectTransmits to 0 [RFC4862].

IPv4-compatible aero addresses are allocated as fe80::ffff:[v4addr], i.e., fe80::/10, followed by 70 '0' bits, followed by 16 '1' bits, followed by a 32bit IPv4 address. IPv4 address usage is outside the scope of this document.

8. Address Mapping - Unicast

Aero interfaces maintain a neighbor cache for tracking per-neighbor state and use the link-local address format specified in Section 7. IPv6 Neighbor Discovery (ND) [RFC4861] messages on aero interfaces observe the native Source/Target Link-Layer Address Option (S/TLLAO) formats of the underlying ANET interfaces (e.g., for Ethernet the S/ TLLAO is specified in [RFC2464]).

MNs such as aircraft typically have many wireless data link types (e.g. satellite-based, cellular, terrestrial, air-to-air directional,

etc.) with diverse performance, cost and availability properties. The aero interface would therefore appear to have multiple link layer connections, and may include information for multiple ANET interfaces in a single message exchange.

Aero interfaces use a new IPv6 ND option called the "Aero Registration Option (ARO)". MNs invoke the MS by including an ARO in Router Solicitation (RS) and (unsolicited) Neighbor Advertisement (NA) messages, and the MS includes an ARO in unicast Router Advertisement (RA) responses to an RS.

RS/NA messages sent by the MN include AROs formatted as shown 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
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |      Type     |     Length    | Prefix Length |R|  Reserved   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |   ifIndex[1]  |   ifType[1]   |   Flags [1]   |Link[1]|QoS[1] |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P00|P01|P02|P03|P04|P05|P06|P07|P08|P09|P10|P11|P12|P13|P14|P15|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P16|P17|P18|P19|P20|P21|P22|P23|P24|P25|P26|P27|P28|P29|P30|P31|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P32|P33|P34|P35|P36|P37|P38|P39|P40|P41|P42|P43|P44|P45|P46|P47|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P48|P49|P50|P51|P52|P53|P54|P55|P56|P57|P58|P59|P60|P61|P62|P63|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |   ifIndex[2]  |   ifType[2]   |   Flags [2]   |Link[2]|QoS[2] |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P00|P01|P02|P03|P04|P05|P06|P07|P08|P09|P10|P11|P12|P13|P14|P15|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P16|P17|P18|P19|P20|P21|P22|P23|P24|P25|P26|P27|P28|P29|P30|P31|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P32|P33|P34|P35|P36|P37|P38|P39|P40|P41|P42|P43|P44|P45|P46|P47|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P48|P49|P50|P51|P52|P53|P54|P55|P56|P57|P58|P59|P60|P61|P62|P63|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   ...                            ...                            ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |   ifIndex[N]  |   ifType[N]   |   Flags [N]   |Link[N]|QoS[N] |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P00|P01|P02|P03|P04|P05|P06|P07|P08|P09|P10|P11|P12|P13|P14|P15|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P16|P17|P18|P19|P20|P21|P22|P23|P24|P25|P26|P27|P28|P29|P30|P31|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P32|P33|P34|P35|P36|P37|P38|P39|P40|P41|P42|P43|P44|P45|P46|P47|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |P48|P49|P50|P51|P52|P53|P54|P55|P56|P57|P58|P59|P60|P61|P62|P63|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                          zero-padding                         |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: Aero Registration Option (ARO) Format in RS/NA Messages

In this format:

o Type is set to TBD.

- o Length is set to the number of 8 octet blocks in the option (with zero-padding added to the end of the option if necessary to produce an integral number of 8 octet blocks).

- o Prefix Length is set to the length of the MNP embedded in the MN's aero address.

- o R (the "Register" bit) is set to '1' to assert the MNP registration or set to '0' to request de-registration.

- o Reserved is set to the value '0' on transmission.

- o A set of N ANET interface "ifIndex-tuples" are included as follows:

  * ifIndex[i] is set to an 8-bit integer value corresponding to a specific underlying ANET interface. The first ifIndex-tuple MUST correspond to the ANET interface over which the message is sent. Once the MN has assigned an ifIndex to an ANET interface, the assignment MUST remain unchanged while the MN remains registered in the network. MNs MUST number each ifIndex with a value between '1' and '255' that represents a MN-specific 8-bit mapping for the actual ifIndex value assigned to the ANET interface by network management [RFC2863].

  * ifType[i] is set to an 8-bit integer value corresponding to the underlying ANET interface identified by ifIndex. The value represents an aero interface-specific 8-bit mapping for the actual IANA ifType value assigned to the ANET interface by network management [RFC2863].

  * Flags[i] is an 8-bit flags field. All flag bits are currently undefined and set to the value '0' on transmission. Future updates may specify new flags.

  * Link[i] encodes a 4-bit link metric. The value '0' means the link is DOWN, and the remaining values mean the link is UP with metric ranging from '1' ("low") to '15' ("high").

  * QoS[i] encodes the number of 4-byte blocks (between '0' and '15') of two-bit P[i] values that follow. The first 4 blocks correspond to the 64 Differentiated Service Code Point (DSCP) values P00 - P63 [RFC2474]. If additional 4-byte P[i] blocks follow, their values correspond to "pseudo-DSCP" values P64, P65, P66, etc. numbered consecutively. The pseudo-DSCP values correspond to ancillary QoS information defined for the specific aero interface (e.g., see Appendix A).

* P[i] includes zero or more per-ifIndex 4-byte blocks of two-bit Preferences. Each P[i] field is set to the value '0' ("disabled"), '1' ("low"), '2' ("medium") or '3' ("high") to indicate a QoS preference level for ANET interface selection purposes. The first four blocks always correspond to the 64 DSCP values. If one or more of the blocks are absent (e.g., for QoS values 0,1,2,3) the P[i] values for the missing blocks default to "medium".

Unicast RA messages sent by the MS in response to MN RS messages include AROs formatted as shown in Figure 4:

```
 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 = 1   | Prefix Length |R|  Reserved   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    ifIndex    |    ifType     |     Flags     | Link  |  QoS  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4: Aero Registration Option (ARO) Format in RA messages

In this format:

o Type is set to TBD.

o Length is set to the constant value '1' (i.e., 1 unit of 8 octets).

o Prefix Length is set to the length associated with the aero address of the destination MN.

o R is set to '1' to confirm registration or set to '0' to release/ decline registration.

o ifIndex, ifType, Flags, Link and QoS echo the values of the same fields that were received in the first ifIndex-tuple of the soliciting RS. The echoed values provide a nonce that allows the MN to associate the received RA with the soliciting RS.

9. Address Mapping - Multicast

The multicast address mapping of the native underlying ANET interface applies. The mobile router on board the aircraft also serves as an IGMP/MLD Proxy for its EUNs and/or hosted applications per [RFC4605] while using the link layer address of the router as the link layer address for all multicast packets.

10. Address Mapping for IPv6 Neighbor Discovery Messages

Per [RFC4861], IPv6 ND messages may be sent to either a multicast or unicast link-scoped IPv6 destination address. However, IPv6 ND messaging must be coordinated between the MN and MS only without invoking other nodes on the ANET.

For this reason, ANET links maintain unicast link-layer addresses ("MSADDR") for the purpose of supporting MN/MS IPv6 ND messaging. For Ethernet-compatible ANETs, this specification reserves one Ethernet unicast address 00-00-5E-00-52-14. For non-Ethernet statically-addressed ANETs, MSADDR is reserved per the assigned numbers authority for the ANET addressing space. For still other ANETs, MSADDR may be dynamically discovered through other means, e.g., link-layer beacons.

MNs map all IPv6 ND messages they send (i.e., both multicast and unicast) to an MSADDR instead of to an ordinary unicast or multicast link-layer address. In this way, all of the MN's IPv6 ND messages will be received by MS devices that are configured to accept packets destined to MSADDR. Note that multiple MS devices on the link could be configured to accept packets destined to MSADDR, e.g., as a basis for supporting redundancy.

Therefore, ARs MUST accept and process packets destined to MSADDR, while all other devices MUST NOT process packets destined to MSADDR. This model has a well-established operational experience in Proxy Mobile IPv6 (PMIP) [RFC5213][RFC6543].

11. Conceptual Sending Algorithm

The MN's IPv6 layer selects the outbound aero interface according to standard IPv6 requirements. The aero interface maintains default routes and neighbor cache entries for MSEs, and may also include additional neighbor cache entries created through other means (e.g., Address Resolution, static configuration, etc.).

After a packet enters the aero interface, an outbound ANET interface is selected based on traffic engineering information such as DSCP, application port number, cost, performance, message size, etc. Aero interface traffic engineering could also be configured to perform replication across multiple ANET interfaces for increased reliability at the expense of packet duplication.

11.1. Multiple Aero Interfaces

MNs may associate with multiple MS instances concurrently. Each MS instance represents a distinct aero link distinguished by its associated MSPs. The MN configures a separate aero interface for each link so that multiple interfaces (e.g., aero0, aero1, aero2, etc.) are exposed to the IPv6 layer.

Depending on local policy and configuration, an MN may choose between alternative active aero interfaces using a packet's DSCP, routing information or static configuration. Interface selection based on per-packet source addresses is also enabled when the MSPs for each aero interface are known (e.g., discovered through Prefix Information Options (PIOs) and/or Route Information Options (RIOs)).

Each aero interface can be configured over the same or different sets of ANET interfaces. Each ANET distinguishes between the different aero links based on the MSPs represented in per-packet IPv6 addresses.

Multiple distinct aero links can therefore be used to support fault tolerance, load balancing, reliability, etc. The architectural model parallels Layer 2 Virtual Local Area Networks (VLANs), where the MSPs serve as (virtual) VLAN tags.

12. Router Discovery and Prefix Registration

ARs process IPv6 ND messages destined to all-routers multicast, subnet router anycast and unicast link-local IPv6 addresses. ARs configure the link-layer address MSADDR (see: Section 10) and act as a proxy for MSE addresses in the range fe80::1 through fe80::ffff:fffe.

MNs interface with the MS by sending RS messages with AROs. For each ANET interface, the MN sends RS messages with AROs with link-layer destination address set to MSADDR and with network-layer destination address set to either a specific MSE aero address, subnet router anycast, or all-routers multicast. The MN discovers MSE addresses either through an RA message response to an initial anycast/multicast RS or before sending an initial RS message. [RFC5214] provides example MSE address discovery methods, including information conveyed during data link login, name service lookups, static configuration, etc.

The AR receives the RS messages and contacts the corresponding MSE. When the MSE responds, the AR returns an RA message with source address set to the MSE address, with an ARO and with any information

for the link that would normally be delivered in a solicited RA message.

MNs configure aero interfaces that observe the properties discussed in the previous section. The aero interface and its underlying interfaces are said to be in either the "UP" or "DOWN" state according to administrative actions in conjunction with the interface connectivity status. An aero interface transitions to UP or DOWN through administrative action and/or through state transitions of the underlying interfaces. When a first underlying interface transitions to UP, the aero interface also transitions to UP. When all underlying interfaces transition to DOWN, the aero interface also transitions to DOWN.

When an aero interface transitions to UP, the MN sends initial RS messages to register its MNP and an initial set of underlying ANET interfaces that are also UP. The MN sends additional RS messages to refresh lifetimes and to register/deregister underlying ANET interfaces as they transition to UP or DOWN.

ARs coordinate with the MSE and return RA messages with configuration information in response to a MN's RS messages. The RAs include a Router Lifetime value and any necessary options, such as:

o PIOs with (A; L=0) that include MSPs for the link [RFC8028].

o RIOs [RFC4191] with more-specific routes.

o an MTU option that specifies the maximum acceptable packet size for the aero link

The AR sends immediate unicast RA responses without delay; therefore, the 'MAX_RA_DELAY_TIME' and 'MIN_DELAY_BETWEEN_RAS' constants for multicast RAs do not apply. The AR MAY send periodic and/or event-driven unsolicited RA messages, but is not required to do so for unicast advertisements [RFC4861].

The MN sends RS messages from within the aero interface while using an UP underlying ANET interface as the outbound interface. Each RS message is formatted as though it originated from the IPv6 layer, but the process is coordinated wholly from within the aero interface and is therefore opaque to the IPv6 layer. The MN sends initial RS messages over an UP underlying interface with its aero address as the source. The RS messages include AROs with a valid Prefix Length as well as ifIndex-tuples appropriate for underlying ANET interfaces. The AR processes RS message and forwards the information in the ARO to the MSE.

When the MSE processes the AR information, if the prefix registration was accepted the MSE injects the MNP into the routing/mapping system then caches the new Prefix Length, MNP and ifIndex-tuples. The MSE then coordinates with the AR to return an RA message to the MN with an ARO with a non-zero Router Lifetime if the prefix assertion was acceptable; otherwise, with a zero Router Lifetime.

When the MN receives the RA message, it creates a default route with next hop address set to the MSE found in the RA source address and with link-layer address set to MSADDR. The AR will then forward packets acting as a proxy between the MN and the MS.

The MN then manages its underlying ANET interfaces according to their states as follows:

- When an underlying ANET interface transitions to UP, the MN sends an RS over the ANET interface with an ARO. The ARO contains a first ifIndex-tuple with values specific to this ANET interface, and may contain additional ifIndex-tuples specific to other ANET interfaces.

- When an underlying ANET interface transitions to DOWN, the MN sends an RS or unsolicited NA message over any UP ANET interface with an ARO containing an ifIndex-tuple for the DOWN ANET interface with Link(i) set to '0'. The MN sends an RS when an acknowledgement is required, or an unsolicited NA when reliability is not thought to be a concern (e.g., if redundant transmissions are sent on multiple ANET interfaces).

- When a MN wishes to release from a current MSE, it sends RS messages over any UP ANET interfaces with an ARO with R set to 0. The corresponding MSE then withdraws the MNP from the routing/mapping system and returns an RA message with an ARO with Router Lifetime set to 0.

- When all of a MNs underlying interfaces have transitioned to DOWN, the MSE withdraws the MNP the same as if it had received a message with an ARO with R set to 0.

The MN is responsible for retrying each RS exchange up to MAX_RTR_SOLICITATIONS times separated by RTR_SOLICITATION_INTERVAL seconds until an RA is received. If no RA is received over multiple UP ANET interfaces, the MN declares this MSE unreachable and tries a different MSE.

The IPv6 layer sees the aero interface as an ordinary IPv6 interface. Therefore, when the IPv6 layer sends an RS message the aero interface returns an internally-generated RA message as though the message

originated from an IPv6 router. The internally-generated RA message contains configuration information (such as Router Lifetime, MTU, etc.) that is consistent with the information received from the RAs generated by the MS.

Whether the aero interface IPv6 ND messaging process is initiated from the receipt of an RS message from the IPv6 layer is an implementation matter. Some implementations may elect to defer the IPv6 ND messaging process until an RS is received from the IPv6 layer, while others may elect to initiate the process independently of any IPv6 layer messaging.

13. Detecting and Responding to MSE Failures

In environments where fast recovery from MSE failure is required, ARs SHOULD use Bidirectional Forwarding Detection (BFD) [RFC5880] to track MSE reachability. Nodes that use BFD can quickly detect and react to failures so that cached information is re-established through alternate paths. BFD control messaging is carried only over well-connected ground domain networks (i.e., and not low-end aeronautical radio links) and can therefore be tuned for rapid response.

ARs establish BFD sessions with MSEs for which there are currently active ANET MNs. If an MSE fails, ARs can quickly inform MNs of the outage by sending RA messages on the ANET interface. The AR sends RA messages with source address set to the MSEs address, destination address set to all-nodes multicast, and Router Lifetime set to 0. The AR SHOULD send MAX_FINAL_RTR_ADVERTISEMENTS RA messages separated by small delays [RFC4861].

Any MNs on the ANET interface that have been using the (now defunct) MSE will receive the RA messages and associate with a new MSE. For this reason, MNs SHOULD maintain multiple MSE associations so that loss of a single MSE does not necessitate immediate ANET interface control message signaling.

14. IANA Considerations

The IANA is instructed to allocate an official Type number from the IPv6 Neighbor Discovery Option Formats registry for the Aero Registration (AR) option. Implementations set Type to 253 as an interim value [RFC4727].

The IANA is instructed to allocate one Ethernet unicast address, 00-00-5E-00-52-14 [RFC5214] in the registry "IANA Ethernet Address Block - Unicast Use".

15. Security Considerations

Security considerations are the same as defined for the specific access network interface types, and readers are referred to the appropriate interface specifications.

IPv6 and IPv6 ND security considerations also apply, and are specified in the normative references.

16. Acknowledgements

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Appendix A. ARO Extensions for Pseudo-DSCP Mappings

Adaptation of the aero interface to specific Internetworks such as the Aeronautical Telecommunications Network with Internet Protocol Services (ATN/IPS) includes link selection preferences based on transport port numbers in addition to the existing DSCP-based preferences. ATN/IPS nodes maintain a map of transport port numbers to additional "pseudo-DSCP" P[i] preference fields beyond the first 64. For example, TCP port 22 maps to pseudo-DSCP value P67, TCP port 443 maps to P70, UDP port 8060 maps to P76, etc. Figure 5 shows an example ARO with extended P[i] values beyond the base 64 used for DSCP mapping (i.e., for QoS values 5 or greater):

```
 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     | Prefix Length |R|   Reserved  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    ifIndex    |    ifType     |     Flags     | Link  |QoS=5+ |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|P00|P01|P02|P03|P04|P05|P06|P07|P08|P09|P10|P11|P12|P13|P14|P15|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|P16|P17|P18|P19|P20|P21|P22|P23|P24|P25|P26|P27|P28|P29|P30|P31|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|P32|P33|P34|P35|P36|P37|P38|P39|P40|P41|P42|P43|P44|P45|P46|P47|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|P48|P49|P50|P51|P52|P53|P54|P55|P56|P57|P58|P59|P60|P61|P62|P63|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|P64|P65|P66|P67|P68|P69|P70|P71|P72|P73|P74|P75|P76|P77|P78|P79|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
...
```

Figure 5: ATN/IPS Extended Aero Option Format

Appendix B. Prefix Length Considerations

The 64-bit boundary in IPv6 addresses [RFC7421] determines the MN aero address format for encoding the most-significant 64 MNP bits into the least-significant 64 bits of the prefix fe80::/64 as discussed in Section 7.

[RFC4291] defines the link-local address format as fe80::/10,followed by 54 unused bits, followed by the least-significant 64 bits of the address. If the 64-bit boundary is relaxed through future standards activity, then the 54 unused bits can be employed for extended coding of MNPs of length /65 up to /118.

The extended coding format would continue to encode MNP bits 0-63 in bits 64-127 of the aero address, while including MNP bits 64-117 in bits 10-63. For example, the aero address corresponding to the MNP 2001:db8:1111:2222:3333:4444:5555::/112 would be fe8c:ccd1:1115:5540:2001:db8:1111:2222, and would still be a valid IPv6 link-local unicast address per [RFC4291].

Appendix C. VDL Mode 2 Considerations

ICAO Doc 9776 is the "Technical Manual for VHF Data Link Mode 2" (VDLM2) that specifies an essential radio frequency data link service for aircraft and ground stations in worldwide civil aviation air traffic management. The VDLM2 link type is "multicast capable" [RFC4861], but with considerable differences from common multicast links such as Ethernet and IEEE 802.11.

First, the VDLM2 link data rate is only 31.5Kbps - multiple orders of magnitude less than most modern wireless networking gear. Second, due to the low available link bandwidth only VDLM2 ground stations (i.e., and not aircraft) are permitted to send broadcasts, and even so only as compact layer 2 "beacons". Third, aircraft employ the services of ground stations by performing unicast RS/RA exchanges upon receipt of beacons instead of listening for multicast RA messages and/or sending multicast RS messages.

This beacon-oriented unicast RS/RA approach is necessary to conserve the already-scarce available link bandwidth. Moreover, since the numbers of beaconing ground stations operating within a given spatial range must be kept as sparse as possible, it would not be feasible to have different classes of ground stations within the same region observing different protocols. It is therefore highly desirable that all ground stations observe a common language of RS/RA as specified in this document.

Appendix D. Change Log

<< RFC Editor - remove prior to publication >>

Differences from draft-templin-atn-aero-interface-07 to draft-templin-atn-aero-interface-08:

- Removed "Classic" and "MS-enabled" link model discussion

- Added new figure for MN/AR/MSE model.

- New Section on "Detecting and responding to MSE failure".

Differences from draft-templin-atn-aero-interface-06 to draft-templin-atn-aero-interface-07:

- Removed "nonce" field from AR option format. Applications that require a nonce can include a standard nonce option if they want to.

- Various editorial cleanups.

Differences from draft-templin-atn-aero-interface-05 to draft-templin-atn-aero-interface-06:

- New Appendix C on "VDL Mode 2 Considerations"

- New Appendix D on "RS/RA Messaging as a Single Standard API"

- Various significant updates in Section 5, 10 and 12.

Differences from draft-templin-atn-aero-interface-04 to draft-templin-atn-aero-interface-05:

- Introduced RFC6543 precedent for focusing IPv6 ND messaging to a reserved unicast link-layer address

- Introduced new IPv6 ND option for Aero Registration

- Specification of MN-to-MSE message exchanges via the ANET access router as a proxy

- IANA Considerations updated to include registration requests and set interim RFC4727 option type value.

Differences from draft-templin-atn-aero-interface-03 to draft-templin-atn-aero-interface-04:

- Removed MNP from aero option format - we already have RIOs and PIOs, and so do not need another option type to include a Prefix.

- Clarified that the RA message response must include an aero option to indicate to the MN that the ANET provides a MS.

- MTU interactions with link adaptation clarified.

Differences from draft-templin-atn-aero-interface-02 to draft-templin-atn-aero-interface-03:

- Sections re-arranged to match RFC4861 structure.

- Multiple aero interfaces

- Conceptual sending algorithm

Differences from draft-templin-atn-aero-interface-01 to draft-templin-atn-aero-interface-02:

- Removed discussion of encapsulation (out of scope)

- Simplified MTU section

- Changed to use a new IPv6 ND option (the "aero option") instead of S/TLLAO

- Explained the nature of the interaction between the mobility management service and the air interface

Differences from draft-templin-atn-aero-interface-00 to draft-templin-atn-aero-interface-01:

- Updates based on list review comments on IETF 'atn' list from 4/29/2019 through 5/7/2019 (issue tracker established)

- added list of opportunities afforded by the single virtual link model

- added discussion of encapsulation considerations to Section 6

- noted that DupAddrDetectTransmits is set to 0

- removed discussion of IPv6 ND options for prefix assertions. The aero address already includes the MNP, and there are many good reasons for it to continue to do so. Therefore, also including the MNP in an IPv6 ND option would be redundant.

- Significant re-work of "Router Discovery" section.

- New Appendix B on Prefix Length considerations

First draft version (draft-templin-atn-aero-interface-00):

- Draft based on consensus decision of ICAO Working Group I Mobility Subgroup March 22, 2019.

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