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Network Mobility Route Optimization Requirements for Operational Use in Aeronautics and Space Exploration Mobile Networks

Abstract

This document describes the requirements and desired properties of Network Mobility (NEMO) Route Optimization techniques for use in global-networked communications systems for aeronautics and space exploration.

Substantial input to these requirements was given by aeronautical communications experts outside the IETF, including members of the International Civil Aviation Organization (ICAO) and other aeronautical communications standards bodies.

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1. Introduction

As background, the Network Mobility (NEMO) terminology and NEMO goals and requirements documents are suggested reading ([4], [5]).

The base NEMO standard [1] extends Mobile IPv6 [2] for singular mobile hosts in order to be used by Mobile Routers (MRs) supporting entire mobile networks. NEMO allows mobile networks to efficiently remain reachable via fixed IP address prefixes no matter where they relocate within the network topology. This is accomplished through the maintenance of a bidirectional tunnel between a NEMO MR and a NEMO-supporting Home Agent (HA) placed at some relatively stable point in the network. NEMO does not provide Mobile IPv6's Route Optimization (RO) features to Mobile Network Nodes (MNNs) other than to the NEMO MR itself. Corresponding Nodes (CNs) that communicate

with MNNs behind an MR do so through the HA and the bidirectional Mobile Router - Home Agent (MRHA) tunnel. Since the use of this tunnel may have significant drawbacks [6], RO techniques that allow a more direct path between the CN and MR to be used are highly desirable.

For decades, mobile networks of some form have been used for communications with people and avionics equipment on board aircraft and spacecraft. These have not typically used IP, although architectures are being devised and deployed based on IP in both the aeronautics and space exploration communities (see Appendix A and Appendix B for more information). An aircraft or spacecraft generally contains many computing nodes, sensors, and other devices that are possible to address individually with IPv6. This is desirable to support network-centric operations concepts. Given that a craft has only a small number of access links, it is very natural to use NEMO MRs to localize the functions needed to manage the large onboard network's reachability over the few dynamic access links. On an aircraft, the nodes are arranged in multiple, independent networks, based on their functions. These multiple networks are required for regulatory reasons to have different treatments of their air-ground traffic and must often use distinct air-ground links and service providers.

For aeronautics, the main disadvantage of using NEMO bidirectional tunnels is that airlines operate flights that traverse multiple continents, and a single plane may fly around the entire world over a span of a couple days. If a plane uses a static HA on a single continent, then for a large percentage of the time, when the plane is not on the same continent as the HA, a great amount of delay is imposed by using the MRHA tunnel. Avoiding the delay from unnecessarily forcing packets across multiple continents is the primary goal of pursuing NEMO RO for aeronautics.

Other properties of the aeronautics and space environments amplify the known issues with NEMO bidirectional MRHA tunnels [6] even further.

- Longer routes leading to increased delay and additional infrastructure load:
  - In aeronautical networks (e.g., using "Plain Old" Aircraft Communication Addressing and Reporting System (ACARS) or ACARS over VHF Data Link (VDL) mode 2) the queueing delays are often long due to Automatic Repeat Request (ARQ) mechanisms and underprovisioned radio links. Furthermore, for space exploration and for aeronautical communications systems that pass through geosynchronous satellites, the propagation delays are also long. These delays, combined with the additional need

to cross continents in order to transport packets between ground stations and CNs, mean that delays are already quite high in aeronautical and space networks without the addition of an MRHA tunnel. The increased delays caused by MRHA tunnels may be unacceptable in meeting Required Communication Performance [7].

Increased packet overhead:
Given the constrained link bandwidths available in even future communications systems for aeronautics and space exploration, planners are extremely adverse to header overhead. Since any amount of available link capacity can be utilized for extra situational awareness, science data, etc., every byte of header/tunnel overhead displaces a byte of useful data.

Increased chances of packet fragmentation:
RFC 4888 [6] identifies fragmentation due to encapsulation as an artifact of tunneling. While links used in the aeronautics and space domains are error-prone and may cause loss of fragments on the initial/final hop(s), considerations for fragmentation along the entire tunneled path are the same as for the terrestrial domain.

Increased susceptibility to failure:
The additional likelihood of either a single link failure disrupting all communications or an HA failure disrupting all communications is problematic when using MRHA tunnels for command and control applications that require high availability for safety-of-life or safety-of-mission.

For these reasons, an RO extension to NEMO is highly desirable for use in aeronautical and space networking. In fact, a standard RO mechanism may even be necessary before some planners will seriously consider advancing use of the NEMO technology from experimental demonstrations to operational use within their communications architectures. Without an RO solution, NEMO is difficult to justify for realistic operational consideration.

In Section 2 we describe the relevant high-level features of the access and onboard networks envisioned for use in aeronautics and space exploration, as they influence the properties of usable NEMO RO solutions. Section 3 then lists the technical and functional characteristics that are absolutely required of a NEMO RO solution for these environments, while Section 4 lists some additional characteristics that are desired but not necessarily required. In Appendix A and Appendix B we provide brief primers on the specific operational concepts used in aeronautics and space exploration, respectively, for IP-based network architectures.

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 [3]. Although this document does not specify an actual protocol, but rather specifies just the requirements for a protocol, it still uses the RFC 2119 language to make the requirements clear.

2. NEMO RO Scenarios

To motivate and drive the development of the requirements and desirable features for NEMO RO solutions, this section describes some operational characteristics to explain how access networks, HAs, and CNs are configured and distributed geographically and topologically in aeronautical and space network architectures. This may be useful in determining which classes of RO techniques within the known solution space [8] are feasible.

2.1. Aeronautical Communications Scenarios

Since aircraft may be simultaneously connected to multiple ground access networks using diverse technologies with different coverage properties, it is difficult to say much in general about the rate of changes in active access links and care-of addresses (CoAs). As one data point, for using VDL mode 2 data links, the length of time spent on a single access channel varies depending on the stage of flight. On the airport surface, VDL mode 2 access is stable while a plane is unloaded, loaded, refueled, etc., but other wired and wireless LAN links (e.g. local networks available while on a gate) may come and go. Immediately after takeoff and before landing, planes are in the terminal maneuvering area for approximately 10 minutes and stably use another VDL mode 2 channel. During en route flight, handovers between VDL mode 2 channels may occur every 30 to 60 minutes, depending on the exact flight plan and layout of towers, cells, and sectors used by a service provider. These handovers may result in having a different access router and a change in CoA, though the use of local mobility management (e.g., [9]) may limit the changes in CoA to only handovers between different providers or types of data links.

The characteristics of a data flow between a CN and MNN varies both depending on the data flow’s domain and on the particular application within the domain. Even within the three aeronautical domains described below, there are varying classes of service that are regulated differently (e.g., for emergencies versus nominal operations), but this level of detail has been abstracted out for the purposes of this document. It is assumed that any viable NEMO RO solution will be able to support a granularity of configuration with many sub-classes of traffic within each of the specific domains listed here.

2.1.1. Air Traffic Services Domain

The MNNs involved in Air Traffic Services (ATS) consist of pieces of avionics hardware on board an aircraft that are used to provide navigation, control, and situational awareness. The applications run by these MNNs are mostly critical to the safety of the lives of the passengers and crew. The MNN equipment may consist of a range of devices from typical laptop computers to very specialized avionics devices. These MNNs will mostly be Local Fixed Nodes (LFNs), with a few Local Mobile Nodes (LMNs) to support Electronic Flight Bags, for instance. It can be assumed that Visiting Mobile Nodes (VMNs) are never used within the ATS domain.

An MR used for ATS will be capable of using multiple data links (at least VHF-based, satellite, HF-based, and wired), and will likely be supported by a backup unit in the case of failure, leading to a case of a multihomed MR that is at least multi-interfaced and possibly multi-prefixed as well, in NEMO terminology.

The existing ATS link technologies may be too anemic for a complete IP-based ATS communications architecture (link technologies and acronyms are briefly defined in Appendix A). At the time of this writing, the ICAO is pursuing future data link standards that support higher data rates. Part of the problem is limited spectrum, pursued under ICAO ACP-WG-F, "Spectrum Management", and part of the problem is the data link protocols themselves, pursued under ICAO ACP-WG-T, "Future Communications Technology". ACP-WG-T has received inputs from studies on a number of potential data link protocols, including B-AMC, AMACS, P34, LDL, WCDMA, and others. Different link technologies may be used in different stages of flight, for instance 802.16 in the surface and terminal area, P34 or LDL en route, and satcom in oceanic flight. Both current and planned data links used for Passenger Information and Entertainment Services (PIES) and/or Airline Operational Services (AOS), such as the satcom links employed by passenger Internet-access systems, support much higher data rates than current ATS links.

Since, for ATS, the MRs and MNNs are under regulatory control and are actively tested and maintained, it is not completely unreasonable to assume that special patches or software be run on these devices to enable NEMO RO. In fact, since these devices are accessed by skilled technicians and professionals, it may be that some special configuration is required for NEMO RO. Of course, simplicity in set up and configuration is highly preferable, however, and the desirable feature labeled "Des1" later in this document prefers solutions with lower configuration state and overhead. To minimize costs of

ownership and operations, it is also highly desirable for only widely available, off-the-shelf operating systems or network stacks to be required, but this is not a full requirement.

Data flows from the ATS domain may be assumed to consist mainly of short transactional exchanges, such as clearance requests and grants. Future ATS communications are likely to include longer messages and higher message frequencies for positional awareness and trajectory intent of all vehicles in motion at the airport and all aircraft within a thirty-mile range during flight. Many of these may be aircraft-to-aircraft, but the majority of current exchanges are between the MNNs and a very small set of CNs within a control facility and take place at any time due to the full transfer of control as a plane moves across sectors of airspace. The set of CNs may be assumed to be topologically close to one another. These CNs are also involved in other data flows over the same access network that the MR is attached to, managing other flights within the sector. These CNs are often geographically and topologically much closer to the MR in comparison to a single fixed HA.

The MNNs and CNs used for ATS will support IP services, as IP is the basis of the new Aeronautical Telecommunications Network (ATN) architecture being defined by ICAO. Some current ATS ground systems run typical operating systems, like Solaris, Linux, and Windows, on typical workstation computer hardware. There is some possibility for an RO solution to require minor changes to these CNs, though it is much more desirable if completely off-the-shelf CN machines and operating systems can be used. Later in this document, the security requirements suggest that RO might be performed with mobility anchors that are topologically close to the CNs, rather than directly to CNs themselves. This could possibly mean that CN modifications are not required.

During the course of a flight, there are several events for which an RO solution should consider the performance implications:

- Initial session creation with an ATS CN (called "Data Link Logon" in the aeronautical jargon).

- Transfer of control between ATS CNs, resulting in regional differences in where the controlling CN is located.

- Aircraft-initiated contact with a non-controlling ATS CN, which may be located anywhere, without relation to the controlling CN.

- Non-controlling, ATS, CN-initiated contact with the aircraft.

- Aircraft transition between one access link to another, resulting in change of CoA.

- Concurrent use of multiple access links with different care-of addresses.

2.1.2. Airline Operational Services Domain

Data flows for Airline Operational Services (AOS) are not critical to the safety of the passengers or aircraft, but are needed for the business operations of airlines operating flights, and may affect the profitability of an airline's flights. Most of these data flows are sourced by MNNs that are part of the flight management system or sensor nodes on an aircraft, and are terminated at CNs located near an airline's headquarters or operations center. AOS traffic may include detailed electronic passenger manifests, passenger ticketing and rebooking traffic, and complete electronic baggage manifests. When suitable bandwidth is available (currently on the surface when connected to a wired link at a gate), "airplane health information" data transfers of between 10 and several hundred megabytes of data are likely, and in the future, it is expected that the In-Flight Entertainment (IFE) systems may receive movie refreshes of data (e.g., television programming or recent news updates) running into the multi-gigabyte range.

Currently, these flows are often short messages that record the timing of events of a flight, engine performance data, etc., but may be longer flows that upload weather or other supplementary data to an aircraft. In addition, email-like interactive messaging may be used at any time during a flight. For instance, messages can be exchanged before landing to arrange for arrival-gate services to be available for handicapped passengers, refueling, food and beverage stocking, and other needs. This messaging is not limited to landing preparation, though, and may occur at any stage of flight.

The equipment comprising these MNNs and CNs has similar considerations to the equipment used for the ATS domain. A key difference between ATS and AOS is that AOS data flows are routed to CNs that may be much more geographically remote to the aircraft than CNs used by ATS flows, as AOS CNs will probably be located at an airline's corporate data center or headquarters. The AOS CNs will also probably be static for the lifetime of the flight, rather than dynamic like the ATS CNs. An HA used for AOS may be fairly close topologically to the CNs, and RO may not be as big of a benefit for AOS since simple event logging is more typical than time-critical interactive messaging. For the small number of messaging flows, however, the CNs are geographically (but not necessarily topologically) very close to the aircraft, though this depends on how

applications are written -- whether they use centralized servers or exchange messages directly. Additionally, since AOS communication is more advisory in nature than ATS, rather than safety-critical, AOS flows are less sensitive to tunnel inefficiencies than ATS flows. For these reasons, in this document, we consider AOS data flow concerns with RO mechanisms to not be full requirements, but instead consider them desirable properties, which are discussed in Section 4.

Future AOS MNNs and CNs can be expected to implement IPv6 and conform to the new IPv6-based ATN Standards and Recommended Practices (SARPS) that ICAO is defining. AOS CNs have similar hardware and software properties as described for ATS above.

2.1.3. Passenger Services Domain

The MNNs involved in the Passenger Information and Entertainment Services (PIES) domain are mostly beyond the direct control of any single authority. The majority of these MNNs are VMNs and personal property brought on board by passengers for the duration of a flight, and thus it is unreasonable to assume that they be preloaded with special software or operating systems. These MNNs run stock Internet applications like web browsing, email, and file transfer, often through VPN tunnels. The MNNs themselves are portable electronics, such as laptop computers and mobile smartphones capable of connecting to an onboard wireless access network (e.g., using 802.11). To these MNN devices and users, connecting to the onboard network is identical to connecting to any other terrestrial "hotspot" or typical wireless LAN. The MNNs are completely oblivious to the fact that this access network is on an airplane and possibly moving around the globe. The users are not always technically proficient and may not be capable of performing any special configuration of their MNNs or applications.

The largest class of PIES CNs consists of typical web servers and other nodes on the public Internet. It is not reasonable to assume that these can be modified specifically to support a NEMO RO scheme. Presently, these CNs would be mostly IPv4-based, though an increasing number of IPv6 PIES CNs are expected in the future. This document does not consider the problem of IPv4-IPv6 transition, beyond the assumption that either MNNs and CNs are running IPv6 or a transition mechanism exists somewhere within the network.

A small number of PIES MNNs may be LFNs that store and distribute cached media content (e.g., movies and music) or that may provide gaming services to passengers. Due to the great size of the data stored on these LFNs compared to the anemic bandwidth available air-to-ground, these LFNs will probably not attempt to communicate off-board at all during the course of a flight, but will wait to update their content via either high-speed links available on the ground or

removable media inserted by the flight crew. However, if a higher bandwidth link were affordably available, it might be used in-flight for these purposes, but supporting this is not a requirement. Data flows needed for billing passengers for access to content are relatively low bandwidth and are currently done in-flight. The requirements of these data flows are less stringent than those of ATS, however, so they are not specifically considered here.

The PIES domain is not critical to safety-of-life, but is merely an added comfort or business service to passengers. Since PIES applications may consume much more bandwidth than the available links used in other domains, the PIES MNNs may have their packets routed through a separate high-bandwidth link that is not used by the ATS data flows. For instance, several service providers are planning to offer passenger Internet access during flight at DSL-like rates, just as the former Connexion by Boeing system did. Several airlines also plan to offer onboard cellular service to their passengers, possibly utilizing Voice-over-IP for transport. Due to the lack of criticality and the likelihood of being treated independently, in this document, PIES MNN concerns are not considered as input to requirements in Section 3. The RO solution should be optimized for ATS and AOS needs and consider PIES as a secondary concern.

With this in consideration, the PIES domain is also the most likely to utilize NEMO for communications in the near-term, since relatively little regulations and bureaucracy are involved in deploying new technology in this domain and since IP-based PIES systems have previously been developed and deployed (although not using NEMO) [10]. For these reasons, PIES concerns factor heavily into the desirable properties in Section 4, outside of the mandatory requirements.

Some PIES nodes are currently using 2.5G/3G links for mobile data services, and these may be able to migrate to an IP-based onboard mobile network, when available.

2.2. Space Exploration Scenarios

This section describes some features of the network environments found in space exploration that are relevant to selecting an appropriate NEMO RO mechanism. It should be noted that IPv4-based mobile routing has been demonstrated on board the UK-DMC satellite and that the documentation on this serves as a useful reference for understanding some of the goals and configuration issues for certain types of space use of NEMO [11]. This section assumes space use of NEMO within the "near-Earth" range of space (i.e., not for communications between the Earth and Mars or other "deep space" locations). Note that NEMO is currently being considered for use out

to lunar distances. No strong distinction is made here between civilian versus military use, or exploration mission versus Earth-observing or other mission types; our focus is on civilian exploration missions, but we believe that many of the same basic concerns are relevant to these other mission types.

In space communications, a high degree of bandwidth asymmetry is often present, with the uplink from the ground to a craft typically being multiple orders of magnitude slower than the downlink from the craft to the ground. This means that the RO overhead may be negligible on the downlink but significant for the uplink. An RO scheme that minimizes the amount of signaling from CNs to an MN is desirable, since these uplinks may be low-bandwidth to begin with (possibly only several kilobits per second). Since the uplink is used for sending commands, it should not be blocked for long periods while serializing long RO signaling packets; any RO signaling from the CN to MNNs must not involve large packets.

For unmanned space flight, the MNNs on board a spacecraft consist almost entirely of LFN-sensing devices and processing devices that send telemetry and science data to CNs on the ground and actuator devices that are commanded from the ground in order to control the craft. Robotic lunar rovers may serve as VMNs behind an MR located on a lander or orbiter, but these rovers will contain many independent instruments and could probably be configured as an MR and LFNs instead of using a single VMN address.

It can be assumed that for manned spaceflight, at least multiple MRs will be present and online simultaneously for fast failover. These will usually be multihomed over space links in diverse frequency bands, and so multiple access network prefixes can be expected to be in use simultaneously, especially since some links will be direct to ground stations while others may be bent-pipe repeated through satellite relays like the Tracking and Data Relay Satellite System (TDRSS). This conforms to the (n,1,1) or (n,n,1) NEMO multihoming scenarios [12]. For unmanned missions, if low weight and power are more critical, it is likely that only a single MR and single link/prefix may be present, conforming to the (1,1,1) or (1,n,1) NEMO multihoming scenarios [12].

In some modes of spacecraft operation, all communications may go through a single onboard computer (or a Command and Data Handling system as on the International Space Station) rather than directly to the MNNs themselves, so there is only ever one MNN behind an MR that is in direct contact with off-board CNs. In this case, removing the MR and using simple host-based Mobile IPv6 rather than NEMO is possible. However, an MR is more desirable because it could be part of a modular communications adapter that is used in multiple diverse

missions to bridge onboard buses and intelligently manage space links. This is cheaper and leads to faster development time than re-creating these capabilities per-mission if using simple Mobile IPv6 with a single Command and Data Handling node that varies widely between spacecraft. Also, all visions for the future involve network-centric operations where the direct addressability and accessibility of end devices and data is crucial. As network-centric operations become more prevalent, application of NEMO is likely to be needed to increase the flexibility of data flow.

The MRs and MNNs on board a spacecraft are highly customized computing platforms, and adding custom code or complex configurations in order to obtain NEMO RO capabilities is feasible, although it should not be assumed that any amount of code or configuration maintenance is possible after launch. The RO scheme as it is initially configured should continue to function throughout the lifetime of an asset.

For manned space flight, additional MNNs on spacesuits and astronauts may be present and used for applications like two-way voice conversation or video-downlink. These MNNs could be reusable and reconfigured per-flight for different craft or mission network designs, but it is still desirable for them to be able to autoconfigure themselves, and they may move between nested or non-nested MRs during a mission. For instance, if astronauts move between two docked spacecrafts, each craft may have its own local MR and wireless coverage that the suit MNNs will have to reconfigure for. It is desirable if an RO solution can respond appropriately to this change in locality and not cause high levels of packet loss during the transitional period. It is also likely that these MNNs will be part of Personal Area Networks (PANs), and so may appear either directly as MNNs behind the main MR on board or have their own MR within the PAN and thus create a nested (or even multi-level nested) NEMO configuration.

3. Required Characteristics

This section lists requirements that specify the absolute minimal technical and/or functional properties that a NEMO RO mechanism must possess to be usable for aeronautical and space communications.

In the recent work done by the International Civil Aviation Organization (ICAO) to identify viable mobility technologies for providing IP services to aircraft, a set of technical criteria was developed ([13], [14]). The nine required characteristics listed in this document can be seen as directly descended from these ICAO criteria, except here we have made them much more specific and focused for the NEMO technology and the problem of RO within NEMO.

The original ICAO criteria were more general and used for comparing the features of different mobility solutions (e.g., mobility techniques based on routing protocols versus transport protocols versus Mobile IP, etc.). Within the text describing each requirement in this section, we provide the high-level ICAO criteria from which it evolved.

These requirements for aeronautics are generally similar to or in excess of the requirements for space exploration, so we do not add any additional requirements specifically for space exploration. In addition, the lack of a standards body regulating performance and safety requirements for space exploration means that the requirements for aviation are much easier to agree upon and base within existing requirements frameworks. After consideration, we believe that the set of aviation-based requirements outlined here also fully suffices for space exploration.

It is understood that different solutions may be needed for supporting different domains. This may mean either different NEMO RO solutions or different mobility solutions entirely. Divergent solutions amongst the domains are acceptable, though preferably avoided if possible.

An underlying requirement that would be assumed by the use of Mobile IP technology for managing mobility (rather than a higher-layer approach) is that IP addresses used both within the mobile network and by CNs to start new sessions with nodes within the mobile network remain constant throughout the course of flights and operations. For ATS and AOS, this allows the Home Addresses (HoAs) to serve as node identifiers, rather than just locators, and for PIES it allows common persistent applications (e.g., Voice over IP (VoIP) clients, VPN clients, etc.) to remain connected throughout a flight. Prior aeronautical network systems like the prior OSI-based ATN and Connexion by Boeing set a precedent for keeping a fixed Mobile Network Prefix (MNP), though they relied on interdomain routing protocols (IDRP and BGP) to accomplish this, rather than NEMO technology. This requirement applies to the selection in general of a mobility management technology, and not specifically to an RO solution once NEMO has been decided on for mobility management.

3.1. Req1 - Separability

Since RO may be inappropriate for some flows, an RO scheme MUST support configuration by a per-domain, dynamic RO policy database. Entries in this database can be similar to those used in IPsec security policy databases in order to specify either bypassing or utilizing RO for specific flows.

3.1.1. Rationale for Aeronautics - Separability

Even if RO is available to increase the performance of a mobile network's traffic, it may not be appropriate for all flows.

There may also be a desire to push certain flows through the MRHA path, rather than performing RO, to enable them to be easily recorded by a central service.

For these reasons, an RO scheme must have the ability to be bypassed by applications that desire to use bidirectional tunnels through an HA. This desire could be expressed through a policy database similar to the security policy database used by IPsec, for instance, but the specific means of signaling or configuring the expression of this desire by applications is left as a detail for the specific RO specifications.

In addition, it is expected that the use of NEMO technology be decided on a per-domain basis, so that it is possible that, for some domains, separate MRs or even non-NEMO mobility techniques are used. This requirement for an RO policy database only applies to domains that utilize NEMO.

This requirement was derived from ICAO's TC-1 [15] - "The approach should provide a means to define data communications that can be carried only over authorized paths for the traffic type and category specified by the user."

One suggested approach to traffic separation is multi-addressing of the onboard networks, with treatment of a traffic domain determined by the packet addresses used. However, there are other techniques possible for meeting this requirement, and so multi-addressing is not itself a requirement. The Req1 requirement we describe above is intended for separating the traffic within a domain that makes use of NEMO based on flow properties (e.g., short messaging flows vs. longer file transfers or voice flows).

3.2. Req2 - Multihoming

An RO solution MUST support an MR having multiple interfaces and MUST allow a given domain to be bound to a specific interface. It MUST be possible to use different MNPs for different domains.

3.2.1. Rationale for Aeronautics - Multihoming

Multiple factors drive a requirement for multihoming capabilities. For ATS safety-of-life critical traffic, the need for high availability suggests a basic multihoming requirement. The

regulatory and operational difficulty in deploying new systems and transitioning away from old ones also implies that a mix of access technologies may be in use at any given time, and may require simultaneous use. Another factor is that the multiple domains of applications on board may actually be restricted in what data links they are allowed to use, based on regulations and policy; thus, at certain times or locations, PIES data flows may have to use distinct access links from those used by ATS data flows.

This drives the requirement that an RO solution MUST allow for an MR to be connected to multiple access networks simultaneously and have multiple CoAs in use simultaneously. The selection of a proper CoA and access link to use per-packet may be either within or outside the scope of the RO solution. As a minimum, if an RO solution is integrable with the MONAMI6 basic extensions (i.e., registration of multiple CoAs and flow bindings) and does not preclude their use, then this requirement can be considered to be satisfied.

It is not this requirement's intention that an RO scheme itself provide multihoming, but rather simply to exclude RO techniques whose use is not possible in multihomed scenarios.

In terms of NEMO multihoming scenarios [12], it MUST be possible to support at least the (n,1,n) and (n,n,n) scenarios.

This requirement was derived from ICAO's TC-2 - "The approach should enable an aircraft to both roam between and to be simultaneously connected to multiple independent air-ground networks."

3.3. Req3 - Latency

While an RO solution is in the process of setting up or reconfiguring, packets of specified flows MUST be capable of using the MRHA tunnel.

3.3.1. Rationale for Aeronautics - Latency

It is possible that an RO scheme may take longer to set up or involve more signaling than the basic NEMO MRHA tunnel maintenance that occurs during an update to the MR's active CoAs when the set of usable access links changes. During this period of flux, it may be important for applications to be able to immediately get packets onto the ground network, especially considering that connectivity may have been blocked for some period of time while link-layer and NEMO procedures for dealing with the transition occurred. Also, when an application starts for the first time, the RO scheme may not have previous knowledge related to the CN and may need to perform some set

up before an optimized path is available. If the RO scheme blocks packets either through queueing or dropping while it is configuring itself, this could result in unacceptable delays.

Thus, when transitions in the MR's set of active access links occurs, the RO scheme MUST NOT block packets from using the MRHA tunnel if the RO scheme requires more time to set up or configure itself than the basic NEMO tunnel maintenance. Additionally, when an application flow is started, the RO scheme MUST allow packets to immediately be sent, perhaps without the full benefit of RO, if the RO scheme requires additional time to configure a more optimal path to the CN.

This requirement was derived from ICAO's TC-3 - "The approach should minimize latency during establishment of initial paths to an aircraft, during handoff, and during transfer of individual data packets."

3.4. Req4 - Availability

An RO solution MUST be compatible with network redundancy mechanisms and MUST NOT prevent fallback to the MRHA tunnel if an element in an optimized path fails.

An RO mechanism MUST NOT add any new single point of failure for communications in general.

3.4.1. Rationale for Aeronautics - Availability

A need for high availability of connectivity to ground networks arises from the use of IP networking for carrying safety-of-life critical traffic. For this reason, single points of failure need to be avoided. If an RO solution assumes either a single onboard MR, a single HA, or some similar vulnerable point, and is not usable when the network includes standard reliability mechanisms for routers, then the RO technique will not be acceptable. An RO solution also MUST NOT itself imply a single point of failure.

This requirement specifies that the RO solution itself does not create any great new fragility. Although in basic Mobile IPv6 and NEMO deployments, the use of a single HA implies a single point of failure, there are mechanisms enabling the redundancy of HAs (e.g., [16]). It is assumed that some HA-redundancy techniques would be employed to increase robustness in an aeronautical setting. It should also be understood that the use of RO techniques decreases dependence on HAs in the infrastructure and allows a certain level of robustness to HA failures in that established sessions using RO may

be able to operate based on Binding Cache entries even after an HA failure. With RO, an HA failure primarily impacts the ability to connect new application flows to a mobile network.

If a failure occurs in a path selected by an RO technique, then that RO technique MUST NOT prevent fallback to the MRHA path for affected traffic.

This does not mention specific redundancy mechanisms for MRs, HAs, or other networking elements, so as long as some reasonable method for making each component redundant fits within the assumptions of the RO mechanism, this requirement can be considered satisfied.

There is no intention to support "Internet-less" operation through this requirement. When an MR is completely disconnected from the majority of the network with which it is intended to communicate, including its HA, there is no requirement for it to be able to retain any communications involving parties outside the mobile networks managed by itself.

This requirement was derived from ICAO's TC-4 - "The approach should have high availability which includes not having a single point of failure."

3.5. Req5 - Packet Loss

An RO scheme SHOULD NOT cause either loss or duplication of data packets during RO path establishment, usage, or transition, above that caused in the NEMO basic support case. An RO scheme MUST NOT itself create non-transient losses and duplications within a packet stream.

3.5.1. Rationale for Aeronautics - Packet Loss

It is possible that some RO schemes could cause data packets to be lost during transitions in RO state or due to unforeseen packet filters along the RO-selected path. This could be difficult for an application to detect and respond to in time. For this reason, an RO scheme SHOULD NOT cause packets to be dropped at any point in operation, when they would not normally have been dropped in a non-RO configuration.

As an attempt at optimizing against packet loss, some techniques may, for some time, duplicate packets sent over both the MRHA tunnel and the optimized path. If this results in duplicate packets being delivered to the application, this is also unacceptable.

This requirement does not necessarily imply make-before-break in transitioning between links. The intention is that during the handoff period, the RO scheme itself should not produce losses (or duplicates) that would not have occurred if RO had been disabled.

This requirement was derived from ICAO's TC-5 - "The approach should not negatively impact end-to-end data integrity, for example, by introducing packet loss during path establishment, handoff, or data transfer."

It is understood that this may be a requirement that is not easily implementable with regards to RO. Furthermore Req1, Separability, may be sufficient in allowing loss-sensitive and duplicate-sensitive flows to take the MRHA path.

3.6. Req6 - Scalability

An RO scheme MUST be simultaneously usable by the MNNs on hundreds of thousands of craft without overloading the ground network or routing system. This explicitly forbids injection of BGP routes into the global Internet for purposes of RO.

3.6.1. Rationale for Aeronautics - Scalability

Several thousand aircraft may be in operation at some time, each with perhaps several hundred MNNs onboard. The number of active spacecraft using IP will be multiple orders of magnitude smaller than this over at least the next decade, so the aeronautical needs are more stringent in terms of scalability to large numbers of MRs. It would be a non-starter if the combined use of an RO technique by all of the MRs in the network caused ground networks provisioned within the realm of typical long-haul private telecommunications networks (like the FAA's Telecommunications Infrastructure (FTI) or the NASA Integrated Services Network (NISN)) to be overloaded or melt-down under the RO signaling load or amount of rapid path changes for multiple data flows.

Thus, an RO scheme MUST be simultaneously usable by the MNNs on hundreds of thousands of craft without overloading the ground network or routing system. The scheme must also be tolerant to the delay and/or loss of initial packets, which may become more pervasive in future Internet routing and addressing architectures [17].

Since at least one traffic domain (PIES) requires connectivity to the Internet and it is possible that the Internet would provide transport for other domains at some distant point in the future, this requirement explicitly forbids the use of techniques that are known to scale poorly in terms of their global effects, like BGP, for the

purposes of RO. The previous OSI-based ATN system used IDRP and an "island" concept for maintaining connectivity to the mobile network but was not tested on a large scale deployment. The Connexion by Boeing system used BGP announces and withdrawals as a plane moved across the globe in order to maintain connectivity [10]. This was found to contribute to a significant amount of churn in the global Internet routing tables, which is undesirable for a number of reasons, and must be avoided in the future.

This requirement was derived from ICAO's TC-6 - "The approach should be scalable to accommodate anticipated levels of aircraft equipage."

The specific scaling factor for the number of aircraft used in our version of the requirement is an order of magnitude larger than the estimated equipage cited in an ICAO draft letter-of-intent to ARIN for an IPv6 prefix allocation request. There were several other estimates that different groups had made, and it was felt in the IETF that using a larger estimate was more conservative. It should be noted that even with this difference of an order of magnitude, the raw number is still several orders of magnitude lower than that of estimated cellular telephone users, which might use the same protocol enhancements as the cellular industry has also adopted Mobile IP standards.

3.7. Req7 - Efficient Signaling

An RO scheme MUST be capable of efficient signaling in terms of both size and number of individual signaling messages and the ensemble of signaling messages that may simultaneously be triggered by concurrent flows.

3.7.1. Rationale for Aeronautics - Efficient Signaling

The amount of bandwidth available for aeronautical and space communications has historically been quite small in comparison to the desired bandwidth (e.g., in the case of VDL links, the bandwidth is 8 kbps of shared resources). This situation is expected to persist for at least several more years. Links tend to be provisioned based on estimates of application needs (which could well prove wrong if either demand or the applications in use themselves do not follow expectations) and do not leave much room for additional networking protocol overhead. Since every byte of available air-ground link capacity that is used by signaling for NEMO RO is likely to delay bytes of application data and reduce application throughput, it is important that the NEMO RO scheme's signaling overhead scales up much more slowly than the throughput of the flows RO is being performed

on. This way, as higher-rate data links are deployed along with more bandwidth-hungry applications, the NEMO RO scheme will be able to safely be discounted in capacity planning.

Note that in meeting this requirement, an RO technique must be efficient in both the size and number of individual messages that it sends, as well in the ensemble of messages sent at one time (for instance, to give RO to multiple ongoing flows following a handover), in order to prevent storms of packets related to RO.

This requirement was derived from ICAO's TC-7 - "The approach should result in throughput which accommodates anticipated levels of aircraft equipage."

3.8. Req8 - Security

For the ATS/AOS domains, there are three security sub-requirements:

1. The RO scheme MUST NOT further expose MNPs on the wireless link than already is the case for NEMO basic support.

2. The RO scheme MUST permit the receiver of a binding update (BU) to validate an MR's ownership of the CoAs claimed by an MR.

3. The RO scheme MUST ensure that only explicitly authorized MRs are able to perform a binding update for a specific MNP.

For the PIES domain, there are no additional requirements beyond those of normal Internet services and the same requirements for normal Mobile IPv6 RO apply.

3.8.1. Rationale for Aeronautics - Security

The security needs are fairly similar between ATS and AOS, but vary widely between the ATS/AOS domains and PIES. For PIES, the traffic flows are typical of terrestrial Internet use and the security requirements for RO are identical to those of conventional Mobile IPv6 RO. For ATS/AOS, however, there are somewhat more strict requirements, along with some safe assumptions that designers of RO schemes can make. Below, we describe each of these ATS/AOS issues, but do not further discuss PIES RO security.

The first security requirement is driven by concerns expressed by ATS communications engineers. The concern is driven by current air-ground links to a craft and their lack of security, which has allowed eavesdroppers to track individual flights in detail. Protecting the MNP from exposure has been expressed as a requirement by this community, though the security of the RO system should not depend on

secrecy of the MNP. The RO scheme should use some reasonable security mechanisms in order to both protect RO signaling via strong authentication and encrypt the MNP from being visible over air-ground links.

The second security requirement is driven by the risk of flooding attacks that are started by an attacker redirecting an MNP's traffic to some target victim CoA. To protect bindings to bogus CoAs from being sent, the RO scheme must somehow validate that an MR actually possesses any CoAs that it claims. For the purposes of aeronautics, it is safe to assume ingress filtering is in place in the access networks.

To protect against "rogue" MRs or abuse of compromised MRs, the RO scheme MUST be capable of checking that an MR is actually authorized to perform a binding update for a specific MNP. To meet this requirement, it can be assumed that some aeronautical organization authority exists who can provide the required authorization, possibly in the form of a certificate that the MR possesses, signed by the aeronautical authority.

It is also reasonable to assume trust relationships between each MR and a number of mobility anchor points topologically near to its CNs (these anchor points may be owned by the service providers), but it is not reasonable to assume that trust relationships can be established between an MR and any given CN itself. Within the onboard networks for ATS and AOS, it is reasonable to assume that the LFNs and MRs have some trust relationship.

It is felt by many individuals that by the time the IP-based ATN grows into production use, there will be a global ATN-specific Public Key Infrastructure (PKI) usable for ATS, though it is agreed that such a PKI does not currently exist and will take time to develop both technically and politically. This PKI could permit the establishment of trust relationships among any pair of ATS MNNs, MRs, or CNs through certificate paths, in contrast to the more limited amount of trust relationships described in the previous paragraph. While it has been suggested that early test and demonstration deployments with a more limited-scale PKI deployment can be used in the near-term, as a global PKI is developed, some parties still feel that assuming a global PKI may be overly bold in comparison to assuming trust relationships with anchor points. It is always possible to scale the anchor point assumption up if a PKI develops that allows the CNs themselves to become the anchor points. It is not possible to go back down in the other direction if a global PKI never emerges.

This requirement was extrapolated from ICAO's TC-8 - "The approach should be secure" and made more specific with help from the MEXT working group.

3.9. Req9 - Adaptability

Applications using new transport protocols, IPsec, or new IP options MUST be possible within an RO scheme.

3.9.1. Rationale for Aeronautics - Adaptability

The concepts of operations are not fully developed for network-centric command and control and other uses of IP-based networks in aeronautical and space environments. The exact application protocols, data flow characteristics, and even transport protocols that will be used in either transitional or final operational concepts are not completely defined yet, and may even change with deployment experience. The RO solution itself should allow all higher-layer protocols, ports, and options to be used.

This requirement was derived from ICAO's TC-9 - "The approach should be scalable to accommodate anticipated transition to new IP-based communication protocols."

4. Desirable Characteristics

In this section, we identify some of the properties of the system that are not strict requirements due to either being difficult to quantify or to being features that are not immediately needed, but that may provide additional benefits that would help encourage adoption.

4.1. Des1 - Configuration

For ATS systems, complex configurations are known to increase uncertainty in context, human error, and the potential for reaching undesirable (unsafe) states [18]. Since RO alters the communications context between an MNN and CN, it is desirable that a NEMO RO solution be as simple to configure as possible and also easy to automatically disable if an undesirable state is reached.

For CNs at large airports, the Binding Cache state management functions may be simultaneously dealing with hundreds of airplanes with multiple service providers and a volume of mobility events due to arrivals and departures. The ability to have simple interfaces for humans to access the Binding Cache configuration and alter it in case of errors is desirable, if this does not interfere with the RO protocol mechanisms themselves.

4.2. Des2 - Nesting

It is desirable if the RO mechanism supports RO for nested MRs, since it is possible that, for PIES and astronaut spacesuits, PANs with MRs will need to be supported. For oceanic flight, ATS and AOS may also benefit from the capability of nesting MRs between multiple planes to provide a "reachback" to terrestrial ground stations rather than relying solely on lower rate HF or satellite systems. In either case, this mode of operation is beyond current strict requirements and is merely desirable. It is also noted that there are other ways to support these communications scenarios using routing protocols or other means outside of NEMO.

Loop-detection, in support of nesting, is specifically not a requirement at this stage of ATN and space network designs, due to both the expectation that the operational environments are carefully controlled and inherently avoid loops and the understanding that scenarios involving nesting are not envisioned in the near future.

4.3. Des3 - System Impact

Low complexity in systems engineering and configuration management is desirable in building and maintaining systems using the RO mechanism. This property may be difficult to quantify, judge, and compare between different RO techniques, but a mechanism that is perceived to have lower impact on the complexity of the network communications system should be favored over an otherwise equivalent mechanism (with regards to the requirements listed above). This is somewhat different than Des1 (Configuration), in that Des1 refers to operation and maintenance of the system once deployed, whereas Des3 is concerned with the initial design, deployment, transition, and later upgrade path of the system.

4.4. Des4 - VMN Support

At least LFNs MUST be supported by a viable RO solution for aeronautics, as these local nodes are within the ATS and AOS domains. If Mobile IPv6 becomes a popular technology used by portable consumer devices, VMNs within the PIES domain are expected to be numerous, and it is strongly desirable for them to be supported by the RO technique, but not strictly required. LMNs are potentially present in future space exploration scenarios, such as manned exploration missions to the moon and Mars.

4.5. Des5 - Generality

An RO mechanism that is "general purpose", in that it is also readily usable in other contexts outside of aeronautics and space exploration, is desirable. For instance, an RO solution that is usable within Vehicular ad hoc Networks (VANETs) [19] or consumer electronics equipment [20] could satisfy this. The goal is for the technology to be more widely used and maintained outside the relatively small aeronautical networking community and its vendors, in order to make acquisitions and training faster, easier, and cheaper. This could also allow aeronautical networking to possibly benefit from future RO scheme optimizations and developments whose research and development is funded and performed externally by the broader industry and academic communities.

5. Security Considerations

This document does not create any security concerns in and of itself. The security properties of any NEMO RO scheme that is to be used in aeronautics and space exploration are probably much more stringent than for more general NEMO use, due to the safety-of-life and/or national security issues involved. The required security properties are described under Req8 of Section 3 within this document.

Under an assumption of closed and secure backbone networks, the air-ground link is the weakest portion of the network and most susceptible to injection of packets, flooding, and other attacks. Future air-ground data links that will use IP are being developed with link-layer security as a concern. This development can assist in meeting one of this document’s listed security requirements (that MNPs not be exposed on the wireless link), but the other requirements affect the RO technology more directly without regard to the presence or absence of air-ground link-layer security.

When deploying in operational networks where network-layer security may be mandated (e.g., virtual private networks), the interaction between this and NEMO RO techniques should be carefully considered to ensure that the security mechanisms do not undo the route optimization by forcing packets through a less optimal overlay or underlay. For instance, when IPsec tunnel use is required, the locations of the tunnel endpoints can force sub-optimal end-to-end paths to be taken.

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Appendix A. Basics of IP-Based Aeronautical Networking

The current standards for aeronautical networking are based on the ISO OSI networking stack and are referred to as the Aeronautical Telecommunications Network (ATN). While standardized, the ATN has not been fully deployed and seems to be in only limited use compared to its full vision and potential. The International Civil Aviation Organization (ICAO) is a part of the United Nations that produces standards for aeronautical communications. The ICAO has recognized that an ATN based on OSI lacks the widespread commercial network support required for the successful deployment of new, more bandwidth-intensive ATN applications, and has recently been working towards a new IPv6-based version of the ATN.

Supporting mobility in an IP-based network may be vastly different than it is in the OSI-based ATN, which uses the Inter-Domain Routing Protocol (IDRP) to recompute routing tables as mobile networks change topological points of attachment. ICAO recognizes this and has studied various mobility techniques based on link, network, transport, routing, and application protocols [14].

Work done within ICAO has identified the NEMO technology as a promising candidate for use in supporting global, IP-based mobile networking. The main concerns with NEMO have been with its current lack of route optimization support and its potentially complex configuration requirements in a large airport environment with multiple service providers and 25 or more airlines sharing the same infrastructure.

A significant challenge to the deployment of networking technologies to aeronautical users is the low capability of existing air-ground data links for carrying IP-based (or other) network traffic. Due to barriers of spectrum and certification, production of new standards and equipment for the lower layers below IP is slow. Currently operating technologies may have data rates measured in the several kbps range, and it is clear that supporting advanced IP-based applications will require new link technologies to be developed simultaneously with the development of networking technologies appropriate for aeronautics.

In addition to well-known commercial data links that can be adapted for aeronautical use, such as Wideband Code-Division Multiple Access (WCDMA) standards or the IEEE 802.16 standard, several more specialized technologies either exist or have been proposed for air-ground use:

- VHF Data Link (VDL) specifies four modes of operation in the 117.975 - 137 MHz range that are capable of supporting different mixes of digital voice and data at fairly low rates. The low rates are driven by the need to operate within 25 kHz channels internationally allocated for aeronautical use. VDL mode 2 is somewhat widely deployed on aircraft and two global service providers support VDL access networks. Experiences with VDL mode 2 indicate that several kbps of capacity delivered to a craft can be expected in practice, and the use of long timers and a collision avoidance algorithm over a large physical space (designed to operate at 200 nautical miles) limit the performance of IP-based transport protocols and applications.

- Aircraft Communications and Reporting System (ACARS) is a messaging system that can be used over several types of underlying RF data links (e.g., VHF, HF, and satellite relay). ACARS messaging automates the sending and processing of several types of event notifications over the course of a flight. ACARS in general is a higher-level messaging system, whereas the more specific "Plain Old ACARS" (POA) refers to a particular legacy RF interface that the ACARS system employed prior to the adoption of VDL and other data links. Support for IP-based networking and advanced applications over POA is not feasible.

- Broadband Aeronautical Multi-carrier Communications (B-AMC) is a hybrid cellular system that uses multi-carrier CDMA from ground-to-air and Orthogonal Frequency Division Multiplexing (OFDM) in the air-to-ground direction. B-AMC runs in the L-band of spectrum and is adapted from the Broadband-VHF (B-VHF) technology originally developed to operate in the VHF spectrum. L-band use is intended to occupy the space formerly allocated for Distance Measuring Equipment (DME) using channels with greater bandwidth than are available than in the VHF band, where analog voice use will continue to be supported. B-AMC may permit substantially higher data rates than existing deployed air-ground links.

- All-Purpose Multi-Channel Aviation Communications System (AMACS) is an adaptation of the Global System for Mobile Communications (GSM) physical layer to operate in the L-band with 50 - 400 kHz channels and use VDL mode 4’s media access technique. AMACS may permit data rates in the several hundred kbps range, depending on specific channelization policies deployed.

- Project 34 (P34) is a wideband public-safety radio system capable of being used in the L-band. P34 is designed to offer several hundred kbps of capacity specifically for IP-based packet networking. It uses OFDM in 50, 100, or 150 kHz channels and

exact performance will depend on the particular operating band, range (guard time), and channelization plan configured in deployment.

- o L-Band Data Link (LDL) is another proposal using the L-band based on existing technologies. LDL adapts the VDL mode 3 access technique and is expected to be capable of up to 100 kbps.

Appendix B. Basics of IP-based Space Networking

IP itself is only in limited operational use for communicating with spacecraft currently (e.g., the Surry Satellite Technology Limited (SSTL) Disaster Monitoring Constellation (DMC) satellites). Future communications architectures include IP-based networking as an essential building block, however. The Consultative Committee for Space Data Systems (CCSDS) has a working group that is producing a network architecture for using IP-based communications in both manned and unmanned near-Earth missions, and has international participation towards this goal [22]. NASA's Space Communications Architecture Working Group (SCAWG) also has developed an IP-based multi-mission networking architecture [23]. Neither of these is explicitly based on Mobile IP technologies, but NEMO is usable within these architectures and they may be extended to include NEMO when/if the need becomes apparent.

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