THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par l'Institut National des Sciences Appliquées de Toulouse

Présentée et soutenue par

Alexandre TRAN NGUYEN

Le 20 janvier 2021

Routeur embarqué pour les communications critiques aéronautiques en environnement multi liens

Ecole doctorale : **SYSTEMES**

Spécialité : **Informatique et Systèmes Embarqués**

Unité de recherche :
Laboratoire de Recherche ENAC

Thèse dirigée par
Nicolas LARRIEU et Alain PIROVANO

Jury

Mme Hakima CHAOUCHI, Rapporteure
Mme Isabelle CHRISMENT, Rapporteure
M. Cong Duc PHAM, Examinateur
M. Nader MBAREK, Examinateur
M. Nicolas LARRIEU, Co-directeur de thèse
M. Alain PIROVANO, Co-directeur de thèse
M. André-Luc BEYLOT, Président

Acknowledgements

The work presented in this manuscript has been realized in the collaboration with the RESCO team at the ENAC Telecom lab and the Datalink department of Collins Aerospace France.

I first would like to thank my two supervisors: Alain Pirovano, a research professor and the head of the RESCO team, and Nicolas Larrieu, a research professor at the ENAC RESCO team for giving me the opportunity to make this thesis. Their dedication and scientific advice helped me a lot throughout my work.

I also would like to thank Collins Aerospace France for welcoming me during this three years, and particularly my project leader Alain Brossard, my scientific responsible Stéphane Pelleschi, my manager Stéphane Sevestre, head of the Datalink department Marc Venier, and all the Datalink team for their support,the time they spent for my project.

I am also very grateful towards all the jury members: André-Luc Beyot, professor at IRIT/ENSEEIHT, Congduc Pham, professor at Université de Pau, Hakima Chaouchi, professor at TELECOM SudParis, Isabelle Chrisment, professor at TELECOM Nancy, and Nader Mbarek, associate professor at ESIREM Université de Bourgogne. A special thank for Hakima Chaouchi and Isabelle Christment for their time spent on reviewing my thesis.

From a personal and a professional point of view, these three years have been such an amazing experience. This could not have been possible without the amazing people and friends I met at the ENAC. I wish you the best for the rest of your thesis and your career.

To conclude this chapter, I couldn't forget to thank my parents, my family and friends for their support during these three years.

Nomenclature

1NZQTH 1st Non-Zero Quantile

3GPP 3rd Generation Partnership Project

A-E Airborne End-system

A-R Airborne Router

A/G-R Air/Ground-Router

AAA Authentication, Authorization, Accounting/Auditing

AAC Airlines Administrative Control

AC-R Access Ground Router

ACARS Aircraft Communication Addressing and Reporting System

ACL ATC Clearance

ACM ATC Communication Management

ACR Avionics COmmunications Router

AEEC Airlines Electronic Engineering Committee

AeroMACS Aeronautical Mobile Airport Communication System

AHP Analytical Hierarchical Process

ANDSF Access Network Discovery and Selection Function

ANSP Air Navigation Service Provider

AOC Aeronautical Operational Control

APC Aeronautical Passenger Communication

ARINC Aeronautical Radio, Incorporated

ASN Autonomous System Number

AS Autonomous System

ATC Air Traffic Control

ATN/IPS Aeronautical Telecommunication Network over the IP suite

ATNP ATN Panel

ATN Aeronautical Telecommunication Network

ATSC Air Traffic Services Communication

AVLC Aviation VHF Link Control

BGP Boarder Gateway Protocol

CLNP Connectionless Network protocol

CME Central Management Entity

CNN Convolutional Neural Network

CNS/ATM Communication Navigation Surveillance / Air Traffic Management

CN Correspondent Node

CoAP Constrained Application Protocol

CoA Care-of-Address

COCR Communications Operating Concept and Requirements

CPDLP Controller Pilot Datalink Communications

CSMA Carrier Sense Multiple Access

DNS Domain Name System

DSP Datalink Service Provider

EID-to-RLOC End-system Identifier to Routing Locator

EID End-system Identifier

EPC Evolved Core Packet

eTR egress Tunnel Router

FANS Future Air Navigation System

FCI Future Communication Infrastructure

FDD Frequence Division-Duplexing

FEP Front End Processor

FLTPLAN Flight Plan Data

G-LISP Ground LISP

GSIF Ground Station Information Frame

GSM Global System for Mobile Communications

HA Home Agent

HFDL High Frequency Data Link

HIP Host Indentity Protocol

HIT Host Identity Tag

HMIPv6 Hierarchical Mobile IPv6

HMM Hidden Markov Model

HoA Home Address

HP Host Processor

ICAO Internation Civil Aviation Organization

ICMP Internet Control Message Protocol

IDRP Inter-Domain Routering Protocol

IETF Internet Engineering Task Force

INET Open-source communication networks simulation package for OMNeT++

IOT Internet of Things

IPv6 Internet Protocol version 6

ISMP Inter-System Mobility Policies

ISRP Inter-System Routing Policies

IS Intermediate System

iTR ingress Tunnel Router

ITU International Telecommunication Union

LCoA Local Care-of-Address

LDACS L-band Digital Aeronautical Communication System

LEO Low Earth orbit

LIN6 Location Independent Network for IPv6

LISP Locator/Identifier Separation Protocol

LMA Local Mobility Anchor

LSTM Long Short Term Memory

MAC Medium Access Control

MADM Multiple Attributes Decision-Making

MAG Mobile Access Gateway

MAP Mobility Anchor Point

MICS Media Independent Command Service

MIES Media Independent Event Service

MIH Media Independent Handover

MIIS Media Independent Information Service

MIPv6 Mobile IPv6

MN Mobile Node

MRMS Mapping System (Mapping Resolver/Mapping Server

NCC Network Control Center

NDP Neighbor Discovery Protocol

NIC Networn Interface Controller

NOB Next on Busy

OFDM Orthogonal Frequency-Division Multiplexing

OOOI application Out,Off,On,In application

OSI Open Systems Interconnection

OSPF Open Shortest Path First

pBA proxy Binding Advertisement

pBU proxy Binding Update

PMIPv6 Proxy Mobile IPv6

POA Plain Old ACARS

QoS Quality of Service

RA Router Advertisement

RCoA Regional Care-of-Address

RLOC Routing Locator

RNN Recurrent Neural Network

ROCKS Reliable Sockets

RS Router Solicitation

RVS Rendezvous Server

SAP Service Access Point

SARPs Standards and Recommended Practices

SATCOM Satellite Communications

SBB SwiftBroadBand

SBD Short Burst Data

SESAR Single European Sky ATM Research

SIP Session Initiation Protocol

SLM session layer mobility

SMR Solicited-Map-Request

SMSL Session-based Mobile Socket Layer

SQP Signal Quality Parameter

TCN Temporal Neural network

TCP Transfert Control Protocol

TESLA Timed Efficient Stream Loss-Tolerant Authentication

UDP User Datagram Protocol

UMTS Universal Mobile Telecommunications System

VANET Vehicular Network

VDLm2 VHF Data Link mode 2

VHF Very High Frequency

VMS VHF Management System

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

WPAN Wireless Personnal Area Network

WSN Wireless Sensor Network

COTRAC Common Trajectory Coordination

Abstract

Critical aeronautical communications are a major issue for flight safety. For a long time, these have relied solely on voice, which is transmitted via an analog communication system. Given the growth in air traffic, this mean of communication has reached saturation and moreover, it has sometimes shown its limits in terms of understanding voice messages, hence the need to find an alternative method. The development of communication technologies based on digital signals allows text messages to be exchanged over a long distance. Initially reserved for non-critical airline operations, it was quickly adopted for communications between the pilot and the air traffic controller, in order to offload the dedicated radio channel. This is known as Data Link. This system, included in a more global infrastructure called the ATN/OSI, has the double advantage of relieving congestion on the frequencies used, but also of limiting the misunderstanding of certain messages. The next evolutions of this aeronautical communication system based on the IP suite and called ATN/IPS is under development. It will have to solve certain problems by proposing new communication technologies and innovative network solutions that can adapt to the increase in critical air data traffic.

In this thesis, we address several issues related to the development of ATN/IPS. The first one concerns the network mobility of the aircraft. Indeed, the ATN/IPS will gather several operators, each providing their own sub-networks composed of one or more access methods. Given the limited range of some of them, an aircraft necessarily needs to use several of them during a flight. A handover is triggered as soon as an aircraft connects to a new ground station, which in some cases requires a change in routing to the aircraft. We propose to combine and adapt two mobility protocols, PMIPv6 and LISP, to guarantee continuity of critical data transmission while minimizing the impact on the avionics architecture and the radio communication channel. Our solution is compared to a standard IP mobility solution in a simulated network environment and specifically developed under OMNeT++. The results show that our approach reduces the handover delay, while lightening the signaling traffic on the radio channel.

Moreover, in order to propose the best aircraft connectivity, we propose an automation of the selection of the best links in the multilink and ATN/IPS context. Typically, multilink algorithms (or link selection) are split into three parts : collecting link information, deciding which links to use, and using the new links. As the mobility solution proposed in this thesis is also compatible with multilink, we are interested in the first two steps. We propose to use an active method to probe the links and estimate their quality. This approach has the advantage of being independent of

the underlying communication technologies. We then compare three estimation methods based on round trip delay and evaluate the performance of each of them. The first method is based on threshold determination, the second is based on a probabilistic model and the third uses supervised learning. This learning-based method makes it possible to estimate the link over time with good precision. Finally, we propose a link selection algorithm in the case where the primary link no longer meets the quality of service requirements.

Résumé

Jusque dans les années 1980, les communications aéronautiques, entre le pilote et les contrôleurs aériens, permettant de garantir la sécurité du vol se reposaient uniquement sur des échanges vocaux via un système de communication analogique. Rapidement confronté à la croissance du trafic aérien, les canaux radio dédiés à ce genre de communications approchaient leur point de saturation. De plus, ils ont aussi montré certaines limites en terme de compréhension des messages du fait du haut niveau de bruit dans le canal de communication, ce qui pouvait entraîner à des erreurs plus ou moins sévères, d'où la nécessité de trouve de trouver un moyen alternatif de communication. L'essor des technologies de communication basées sur des signaux numériques a permis de déployer dans ce contexte un moyen de communication complémentaire permettant l'échange des messages textuels entre le sol et le bord. Au départ réservé pour les opérations des compagnies aériennes (AOC), il a vite été adopté pour les communications plus critiques (appelé ATS), afin de décharger le canal radio dédié. On parle alors de Data Link. Ce système, inclus dans une infrastructure plus globale appelée ATN/OSI (Aeronautical Telecommunication Network), a l'avantage de désengorger les fréquences utilisées mais aussi de limiter la mauvaise compréhension de certains messages. Le data link, comme les communications vocales, repose sur les systèmes radio dont l'avion est équipé (HF, VHF ou satellite à ce jours). L'ATN/OSI est un système dédié uniquement à l'aéronautique. Ces prochaines évolutions ont pour but de faciliter la mise en place de nouvelles technologies et de rendre leur installations moins coûteuses. En ce sens, les organisations internationales de l'aviation civile ont décidé de baser la prochaine version de l'ATN sur la pile protocolaire IP. A ce jour, ce nouveau réseau sera nommé l'ATN/IPS. La pile IP est une technologie standard de communication, utilisée par la plupart des systèmes de communication depuis une dizaine d'années. Elle facilitera donc l'interconnexion et l'inter-opérabilité du réseau ATN avec les systèmes actuels et futurs. Par ailleurs, le nouveau réseau ATN/IPS devra répondre à des contraintes liées aux applications du service aérien de plus en plus exigeantes (report périodique de données critiques, trajectoire 4D, . . .), et ce toujours dans un contexte de croissance du trafic aérien. Afin de répondre à ces besoins, l'ATN/IPS s'appuie sur des nouvelles technologies de communication et des solutions réseaux innovantes prenant en compte les spécificités du domaine aéronautique.

Cette thèse, en collaboration avec l'Ecole Nationale de l'Aviation Civile (ENAC) et l'industriel Collins Aerospace, a pour but de participer au développement de ce nouveau réseau ATN/IPS et en particulier d'apporter des solutions

aux problématiques réseaux liés au contexte aéronautique. Elle est découpée en 3 parties.

Le chapitre 1 apporte une meilleure compréhension au lecteur sur l'architecture des réseaux aéronautiques existants et sur le nouveau réseau ATN/IPS. Il présente les différentes technologies de communication qui seront introduites dans l'ATN/IPS, dont les réseaux cellulaires VDLm2 et LDACS par exemple. L'évolution des réseaux de communication aéronautiques pour les communications critiques est aussi présenté dans ce chapitre. Enfin, les problématiques réseaux de l'ATN/IPS y sont abordées (dont notamment la mobilité réseau et l'utilisation simultanée des liens sans-fil disponibles), ce qui permettra au lecteur de mieux saisir les enjeux des chapitres suivants.

Le chapitre 2 se consacre au problème de la mobilité IP réseau de l'avion. Ce problème de mobilité dans les réseaux IP est apparu avec les ordinateurs portables et les smartphones, et leur besoin de rester joignable pendant leur déplacement. Cependant la mobilité de l'avion à travers le globe présente de nouvelles problématiques. En effet, le réseau ATN/IPS est composé de plusieurs sous-réseaux de différents types d'accès de façon à couvrir la totalité du globe comme évoqué dans le chapitre 1. Un transfert intercellulaire (ou handoff) est déclenché dès lors qu'un avion se connecte à une nouvelle station sol, entraînant dans certains cas la nécessité de modifier le routage vers celui-ci. On parle alors de handoff intra-domaine lorsque celui-ci se fait à l'intérieur d'un même sous-réseau d'accès et de handoff inter-domaine lorsque qu'il y a le passage d'un sous-réseau d'accès à un autre. L'une des contraintes majeures est que cet handoff doit être transparent vis-à-vis de l'avion de sorte à ce qu'aucun packet ne soit perdu pendant cette étape et que le délai de bout-en-bout ne soit pas impacté. De plus, une autre contrainte toute aussi importante est l'impact du protocole de mobilité. D'une part, celui-ci doit modifier au minimum la pile IP du routeur embarqué pour minimiser le coût et d'autre part les messages protocolaires doivent impacter au minimum le canal radio de communication étant donné les ressources limitées de ce dernier. Après avoir comparé les différents protocoles de mobilité entre eux, nous proposons un nouvelle solution P-LISP qui permet d'associer le protocole Proxy Mobile IPv6 (PMIPv6), une extension du protocole Mobile IPv6 (MIPv6), et LISP (Locator Identifier Separation Protocol). Ces deux protocoles sont des solutions de mobilité basées sur des mécanismes implantés dans le coeur du réseau, allégeant ainsi le développement du routeur embarqué. Le protocole PMIPv6 est une extension du standard MIPv6 pour gérer la mobilité locale des noeuds mobiles dans les réseaux IP, i.e lorsqu'un handoff intra-domaine doit être effectué. Le protocole LISP est une solution de mobilité globale se reposant sur deux espaces d'adressage distincts. Le premier espace EID (End-System Identifier) sert uniquement à identifier les noeuds terminaux et n'est utilisé qu'en bordure du réseau. A l'inverse, l'espace RLOC (Routing Locator) est utilisé au coeur du réseau pour identifier les routeurs tunnels qui sont chargés d'acheminer les paquets de données à l'autre bout du réseau ATN/IPS afin d'atteindre l'espace EID du destinataire. La correspondance entre les deux espaces d'addressage se fait à l'aide d'un système de mapping (Mapping System) qui garde en mémoire l'association entre un EID et une adresse RLOC. Lorsqu'un routeur tunnel a besoin de connaître l'adresse RLOC correspondant à un EID, il effectue une requête au Mapping System.

Nous expliquons comment notre solution peut s'adapter à l'architecture réseau de l'ATN/IPS, puis nous détaillons les différents mécanismes de notre solution afin de montrer comment elle permet de gérer les cas de handoff intra-domaine et inter-domaine. Chaque sous-réseau d'accès dispose d'un Agent local qui a la tâche d'attribuer un Home préfixe à l'avion. Cette étape s'effectue lors du premier attachement de l'avion à un sous-réseau d'accès avant le décollage. Ensuite, lorsqu'un handoff intra-domaine survient, l'agent local est chargé de la mise à jour de la localisation de l'avion dans son domaine réseau, sans pour autant prévenir le reste du réseau ATN/IPS. Les paquets en provenance des entités sols sont toujours acheminés vers cet agent local qui va rediriger les paquets vers le nouveau point d'accès avec l'avion dans son sous-réseau. En revanche lors d'un handoff inter-domaine, il est nécessaire de mettre à jour les tables de routage vers le nouveau sous-réseau d'accès. Pour ce faire, lorsqu'un agent local détecte un nouvel avion dans son sous-réseau, il récupère d'abord le préfixe attribué à l'avion puis se charge d'annoncer au Mapping system situé au coeur du réseau ATN/IPS sa nouvelle association avec l'identifiant EID de l'avion. Le Mapping System informe ensuite, via un mécanisme de multicast, les routeurs qui ont déjà transmis des paquets vers l'avion de sa nouvelle destination, i.e de la nouvelle adresse RLOC rattachée à l'avion. Ces derniers peuvent dès lors établir un nouveau chemin vers le nouveau agent local en charge de rediriger les paquets vers l'avion.

Afin d'évaluer notre proposition, nous avons développé un framework basé sur le simulateur réseau OMNeT++, dans lequel nous implémentons notre solution et nous la comparons avec une solution de mobilité IPv6 standard qui utilise les protocoles MIPv6 et PMIPv6. OMNeT++ ne proposant pas de modules simulant les technologies aéronautiques sans-fil, nous utilisons un modèle de propagation idéale dans lequel nous introduisons un délai de couche 2 représentatif de la technologie VDLm2 (VHF Datalink mode 2), utilisée actuellement dans les réseaux aéronautiques. Nous utilisons un modèle de handoff basé sur la priorité du sous-réseau d'accès, pour modéliser la politique de handoff sur les routeurs embarqués actuels de Airbus (ACR) sur le réseau ATN/OSI. Nous nous intéressons à trois critères qui sont les suivants : la signalisation sur le lien radio, qui est le lien le plus contraignant du réseau, le délai de bout-en-bout des paquets applicatifs et le délai du handoff.

Pour un handoff intra-domaine, les 2 solutions se reposent sur le protocole PMIPv6, qui permet de minimiser l'impact du trafic de signalisation sur le lien radio en le limitant à un échange de découverte de routeur qui est géré par le protocole NDP (Neighbor Discovery Protocol), qui a les même fonctions que le protocole ARP dans IPv4. De ce fait, le délai de handoff dans ce cas-là ne repose que sur l'agent local et du temps qu'il met à créer la nouvelle association avec le nouveau routeur d'accès de l'avion. Ce temps correspond à un délai d'aller-retour entre le nouveau routeur d'accès et l'agent local. En revanche pour un handoff inter-domaine, notre proposition P-LISP obtient de meilleurs résultats que la solution de mobilité standard MIPv6/PMIPv6 sur les trois critères de comparaison. Le premier d'entre eux, la signalisation, est réduit à un simple échange de paquets RS/RA, comme pour le cas du handoff intra-domaine alors qu'avec la solution MIPv6/PMIPv6, il y a en plus un échange entre l'avion et son "Home Agent" (différent de l'agent local). Ce qui se traduit également par un délai de handoff plus long à cause de cette échange supplémentaire. Concernant le délai des paquets applicatifs, dans le scénario considé, les délais sont similaires, car nous supposons que le Home Agent de l'avion se trouve dans la zone de vol de ce dernier, Mais dans des scénarios de mobilité inter-continentale, le protocole MIPv6 peut engendrer des délais de bout-en-bout plus élevés comparé à P-LISP.

La solution que nous proposons permet de gérer la mobilité réseau globale de l'avion tout en minimisant le coût de développement à bord, la signalisation engendrée, et le délai de handoff. De plus, cette solution est compatible avec le scénario de multilink avec l'aide d'une interface réseau supplémentaire au niveau du routeur embarqué pour gérer les différents liens.

Le chapitre 3 se concentre sur une autre problématique du réseau ATN/IPS. L'ATN/IPS sera doté de nombreux sous-réseaux d'accès de différents types. Afin d'optimiser l'usage les ressources radio globales du réseau, les avions devront utiliser au mieux les resources du réseau afin de garantir les délais de bout-en-bout mais aussi d'éviter la congestion du réseau. Pour ce faire, un algorithme de sélection de liens sera implémenté à bord de l'avion. Celui-ci se décompose en trois parties: la collecte d'information, la décision et l'exécution. Dans la littérature, nous trouvons beaucoup de propositions sur les deux dernières parties. En effet, le problème de décision se base sur les problèmes MADM (Multiple Attributes Decision-Making Problem) où un ensemble de paramètres est considéré. Ces problèmes se résolvent en général par des méthodes de fonction poids (Simple Additive Weighting Method), de logique flou (Fuzzy Logic), ou bien de théorie des jeux. La phase d'exécution est résolue avec les protocoles de mobilité, en supposant que celui-ci peut gérer des connexions simultanées. Avec notre solution, un avion peut enregistrer plusieurs localisations (adresse RLOC) dans le Mapping System, ainsi les systèmes peuvent utiliser un de ces liens pour le joindre. A l'inverse, pour les communications bord-sol, l'avion doit implémenter une interface virtuelle pour garder une adresse IPv6 unique correspondant à toutes interfaces. Un module supplémentaire doit dans ce cas-là gérer la sélection de liens entre la couche réseau et la couche Lien de l'avion. Enfin pour la première phase, dans la littérature, la collecte d'information se base sur les informations de couche physique. Lorsque les informations proviennent de plusieurs liens, une entité appellé MIH (Media Independent handoff, IEEE 802.21) qui agit comme une inter-couche de niveau 2.5 s'occupe d'homogénéiser les informations provenant des couches inférieures. Cette entité a été développée au départ pour les technologies 802 et 3GPP. Développer une telle entité pour le monde aéronautique demanderait une adaptation des technologies futures et existantes, et ajouterait une surcouche à bord du routeur embarqué. Pour toutes ces raisons, nous nous concentrons dans ces travaux sur les informations de niveau supérieur pour obtenir l'état des liens radios.

Au niveau des couches supérieures, l'évaluation des liens de communication se fait à l'aide de deux méthodes: une méthode passive et une méthode active. La première méthode repose sur une analyse du trafic existant sur les liens. Cependant, cette méthode est uniquement applicable pour évaluer le lien primaire de communication, mais ne peut pas mesurer la qualité des liens secondaires. C'est pourquoi nous nous reposons sur la deuxième méthode et l'envoi de paquets sonde au niveau applicatif. Ces paquets sont définis par le protocole ICMPv6 pour IPv6. Notre méthode de sonde a pour but d'évaluer que le délai engendré par le lien radio car nous supposons qu'il s'agit du lien le plus instable dans le réseau. Avec l'aide du champ TTL (Time-to-Live), nous parvenons à obtenir un délai d'aller-retour qui est dû uniquement au réseau d'accès. De plus avec l'adresse IP source du paquet ICMPv6 reçu par l'avion, nous pouvons identifier le sous-réseau sur lequel le paquet est passé et donc la technologie d'accès correspondante. A l'aide de ce délai, nous essayons de déterminer la qualité du lien radio utilisé en terme de taux d'utilisation. En effet, un délai plus long est généralement dû à une plus grande occupation du canal. Pour ce faire, nous évaluons trois méthodes d'estimation: une méthode par seuil, une méthode probabiliste basée sur les chaines de Markov cachés (HMM: Hidden Markov Model) et une méthode par apprentissage basée les réseaux de neurones récurrents (LSTM: Long short-term memory).

Notre évaluation est réalisée à l'aide du framework SAPIENT, développé sous OMNeT++ et spécialement conçu dans le cadre de l'ATN/IPS. Il permet de modéliser un environnement dans lequel l'avion peut se connecter à des liens terrestres (LDACS et VDLm2) et satellites. Les technologies LDACS et satellite reposant sur le même protocole d'accès TDMA (Time Division Multiple Access), nous estimons uniquement les deux liens terrestres. La méthode probabiliste n'est pas adaptée à notre cas d'étude car dans les deux cas, l'autocorrélation de la qualité du lien est élevée et ne décroit pas suffisamment vite pour valider l'hypothèse de Markov. Des modèles de chaînes de Markov cachées avec un ordre N plus élevé permettrait sans doute d'avoir de meilleures prédictions. La méthode par seuil est une méthode simple mais qui permet d'avoir une précision de l'ordre de 80% pour le lien LDACS et 75% pour le lien VDLm2. Cependant, ces résultats sont obtenues avec un nombre de classes limitées puisque nous considérons que trois états du lien et cette méthode permet uniquement de prédire la qualité du lien à l'instant présent. Pour la méthode LSTM, dans les mêmes conditions, les résultats sont similaires à la méthode par seuil. Pour aller plus loin, nous avons utilisé le réseau LSTM comme un régresseur pour évaluer la qualité du lien. Nous montrons que cette approche permet de prédire avec le même niveau de précision les futurs états des liens, que ce soit pour la technologie LDACS ou bien VDLm2.

Pour conclure, cette thèse a permis de mener des travaux sur le nouveau réseau aéronautique ATN/IPS qui sera le prochain réseau pour les communications critiques aéronautiques. Cette nouvelle technologie, s'appuyant sur le standard IPv6, propose de nouveaux challenges en termes de mobilité réseau et utilisation des liens sans-fil. Nous proposons le protocole P-LISP pour répondre à la première problématique. Les résultats de simulation montrent qu'il permet de gérer les scénarios de handoff de manière efficiente comparé au protocole standard de mobilité MIPv6 couplé avec PMIPv6. Quant à la deuxième problématique, nous nous intéressons à la collecte de d'information pour prédire la qualité des liens. Dans cet environnement hétérogène, notre méthode permet de faire abstraction des couches d'accès et de ce fait pourra être réutilisée dans le futur lorsque de nouvelles technologie d'accès seront développées pour l'ATN/IPS. Celle-ci repose sur l'envoi de paquets sondes pour estimer la charge du lien d'accès. L'étude de ce délai d'aller-retour permet ensuite prédire la qualité du lien via des techniques d'analyse par apprentissage ou par détection de seuil. Cette méthode a montré des résultats encourageants pour les liens terrestres connus à ce jour que sont LDACS et VDLm2.

Contents

List of Figures

List of Tables

Introduction

1 Civil aviation communication

1.1 From voice to datalink in Aeronautical communication networks

Communication through the voice channel

Voice communication has been the first existing mean of communication between the pilot and the air traffic controller and it still plays an important role nowadays. Typically, in order to grant the minimum separation distance between aircraft, the air traffic controller uses this type of communication to directly inform the pilot of the maneuver to perform. The voice communication mainly uses the analog transmission in the VHF band dedicated for the civil aviation communication ranging from 118MHz to 137MHz. This bandwidth is now divided into 8.33kHz spaced channels, in which all the air navigation services operate. In remote areas, where the aircraft is no more reachable via a VHF base station, the transmission is performed either by HF (High Frequency) or SATCOM (SATellite COMmunication) links.

The beginning of datalink communication

While analog voice is a convenient way for communication, it has some drawbacks, particularly in a very noisy environment. Examples of misunderstanding between the pilot and the controller are very common as shown in the Figure 1 and the Figure 2. The first case depicted in the red rectangles highlights a misinterpretation by the controller on the number of lost engines. The second report shows that around 20% of the number of reports on inaccurate message transmissions is due to voice communication. Motivated by a desire of airlines companies in order to reduce crew workload and also improve efficiency in air-ground communication, new ways of communication have been developed. More precisely in 1978, communication based on text message has been identified as a primary datalink communication. The first digital datalink system to be developed was ACARS (Aircraft Communication Addressing and Reporting System) for transmission of short text messages between the aircraft and the ground end systems. One of the first applications of ACARS were the OOOI application (Out, Off, On, In), which is an operational control application dedicated to measure the crew working time. Later on, other types of datalink applications were defined by the ICAO (International Civil Aviation Organization).

Speedbird Nine: *Mayday, Mayday, Mayday—Speedbird Nine. We have lost all four engines. Out of [Flight Level] 370.*

Jakarta Control: *Speedbird Nine, have you got a problem?*

Speedbird Nine: *Jakarta Control—Speedbird Nine. We have lost all four engines. Now out of 360.*

Jakarta Control: *Speedbird Nine—you have lost number four engine?*

Speedbird Nine: *Jakarta Control—Speedbird Nine has lost* ***all four*** *engines, repeat* ***all four engines!*** *Now descending through Flight Level 350!*

—British Airways B747 emergency
(flight through volcanic ash)
Java, 1982.
(Job, 1996)

Figure 1: British Airways B747 emergency report

Source: PresLoiLoi(CC-BY-SA-3.0) via wikimedia commons

Category	Number of Reports	Definition
Other inaccuracies in content	792	1) Erroneous data (formulation errors) 2) Errors in judgment 3) Conflicting interpretation
Ambiguous phraseology	529	Message composition, phraseology, or presentation could lead to a misinterpretation or misunderstanding by the recipient
Incomplete content	296	Originator failed to provide all the necessary information to the recipient to understand the communication
Inaccurate (transposition)	85	Misunderstanding caused by the sequence of numerals within a message
Misinterpretable (phonetic similarity)	71	Similar-sounding names or numerics led to confusion in meaning or in the identity of the intended recipient
Absent (not sent)	1 ,991	Failure to originate or transmit a required or appropriate message
Untimely transmission	710	Message not useful to the recipient because it arrived too early or too late
Garbled phraseology	171	Content of the message lost or severely distorted to the point where the recipient could not understand the intended message
Absent (equipment failure)	153	Equipment malfunction resulting in a complete loss of a message
Recipient not monitoring	553	Failure to maintain listening watch, proper lookout, or read available correct information

Source: U.S. National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS)

Figure 2: Aviation Safety Report

Source: US National Aeronautics and Space Administration (NASA)

1.2 Classification of air-ground applications

4 types of applications

The annex 10 of the ICAO [Org05] is a regulatory document in which both voice and datalink communications for civil aviation are specified. Particularly, concerning the datalink communication, it describes the 4 following categories of applications:

- ATSC (Air Traffic Services Communication) application : concerns all applications between a pilot and an ATC (Air Traffic Control) center. They are responsible for managing the safety of the flight. They include for instance the air navigation control, the weather observation and forecast information and the aircraft positioning report.

- AOC (Aeronautical Operational Control) application: applies to all airlines applications ”required for the exercise of authority over the initiation, continuation, diversion or termination of flight for safety, regularity and efficiency reasons” (from [Org05]). For instance, applications that send messages regarding the maintenance, the fuel level or the expected arrival time belong to this category.

- AAC (Airlines Administrative Control) application: only aims at communication between the crew and the airline head office that are not of safety and operational concerns. Information such personal crew data (planning, accommodation...) or passenger data (list of passengers, connecting flight...) are included in this category.

- APC (Aeronautical Passenger Communication): which is defined as ”Communication relating to the non-safety voice and data services to passengers and crew members for personal communication”, by Eurocontrol. In this category are found for instance all the entertainment applications as well as call and mails service for passengers.

These categories are classified into safety related and non-safety related applications.

The critical applications

Among all of the categories, the ATSC is the most critical one as it is considered as a safety application, meaning that a failure of an ATSC application may endanger the people on-board. On a lower level of criticality, some AOC applications are highly critical, implying that aircraft may not leave if they do not work properly. In consequence, both of these applications must respond to very stringent QoS requirements in terms of transaction time, continuity, integrity and availability. As an example, the table 1 shows some of the constraints they need to meet during the en-route phase of the flight. These data are provided by the Communications Operating Concept and Requirements (COCR), a document published by Eurocontrol [EtFAAF06]. For the rest of the study, we will only consider these types of applications.

Class	tt_{95} (s)	Continuity (probability per hour of flight)	Availability (probability per hour of flight)	Integrity (error rate per hour of flight)
ATSC	0.78	0.99999992	0.999999999	5.10^{-966}
AOC	13.6	0.996	0.9995	5.10^{-966}

Table 1: Most stringent constraints defined by COCR

1.3 Evolution of the datalink communication

Increase of air traffic

The democratization of air transportation as well as the continuous increase of the daily number of flights have a direct impact on the volume of communication exchanges. This increase concerns not only the voice but also the datalink communications. Therefore, new applications as well as new means of communication need to be developed to provide a more efficient air traffic management in a context of a more congested airspace.

New types of application needs

As an example, some datalink applications provided by the CPDLC (Controller Pilot Datalink Communications), which have been introduced in the 2000s will replace air traffic controller voice commands in order to free voice channels. The CPDLC uses text messages which are displayed and sent over this type of interface, as shown in the Figure 3. Recently, new projects have beencreated to modernize the Air Traffic Management (ATM), namely NextGen and SESAR (Single European Sky ATM Research) in the United States and Europe respectively. For instance, the 4D trajectory concept is a new application that aims at ensuring optimum trajectory for aircraft and minimizing the workload for controllers. This new application will need a real time share of data between the aircraft and ATM centers, as it introduces the integration of time in the aircraft 3D trajectory.

However, the standard voice communication channels and the current datalink channels will reach their saturation point in the 2020s [SS06], meaning that new strategies are needed to cope with increased demands of Air Traffic Management. Datalink communications offer new possibilities to increase the effective capacity of the communication channels and are a promising solution to manage the evolution of the communication needs.

2 Means of datalink communications

2.1 History

POA (Plain Old Acars)

The first datalink system to be deployed is named ACARS, also known as POA (Plain old ACARS). It was developed by a private company in the late 1970s. This name stands for the whole network, from the air-ground link to the ground network architecture. Originally aimed for the airlines, ACARS was also adopted by the air traffic control.

Figure 3: A CPDLC interface in the Boeing B737

Source: PresLoiLoi(CC-BY-SA-3.0) via wikimedia commons

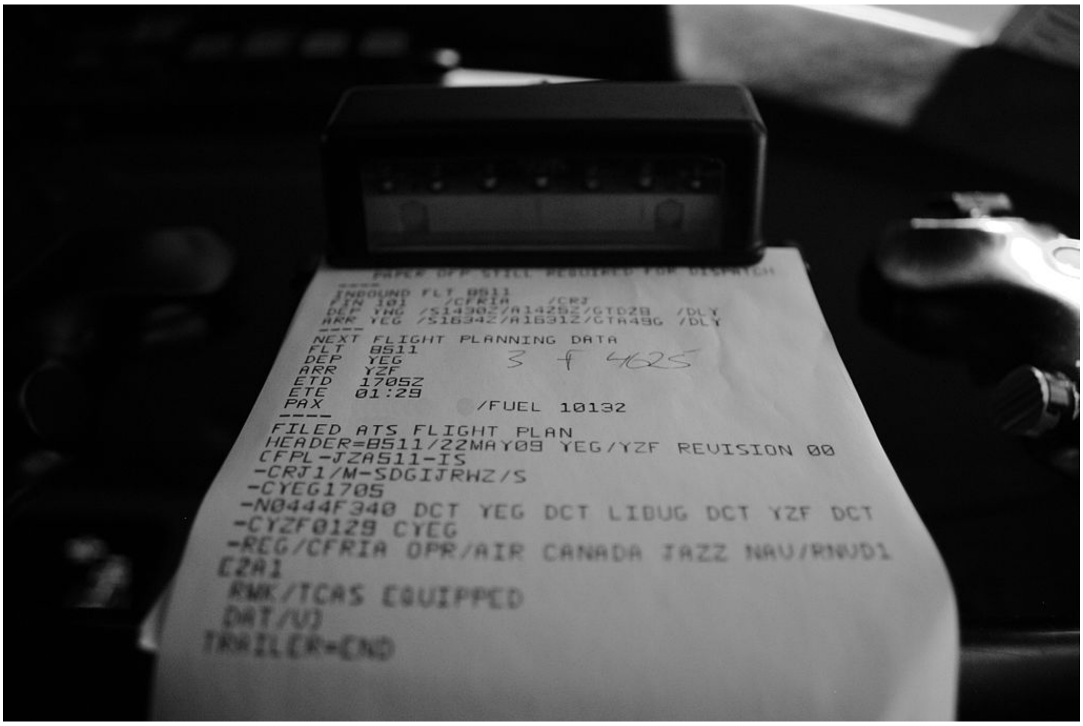


Figure 4: An example of ACARS message

Source: Russavia(CC-BY-SA-2.0) via wikimedia commons

It is a character-oriented and a non-connected system with no quality of service provided. An example of ACARS message is given in the Figure 4.

FANS introduction

Following the introduction of POA, the ICAO created the Future Air Navigation System (FANS) committee in 1983 in order to study and define future air navigation systems. For the air-ground communication perspectives, the committee worked on two main aspects. The first one is the definition of the datalink applications, such as the CPDLC which was introduced previously. However, to be used in the ACARS networks, these highly critical applications need security and reliability functions that are not natively present in ACARS network, as mentioned earlier. In addition, the datalink applications are bit-oriented, while ACARS applications are character-oriented. In consequence, the second working project of the committee has been to define an overlayer to adapt the FANS applications to the ACARS network. This overlay provides the functions of reliability (connected mode, acknowledgements, error detection), a bit/character conversion and an addressing mechanism to allow the aircraft to join the ATC centers. These applications and the overlayer are standardized in the ARINC (Aeronautical Radio, Incorporated) 622 document and aircraft manufacturers proposed certified implementation of this standard. The *Boeing* solution is called *FANS-1* and the *Airbus* is named *FANS-A*, thus the ARINC 622 standard is also called *FANS-1/A*. The implementation of these systems progressively became mandatory so that air traffic controllers can benefit from the advantages of the datalink communications.

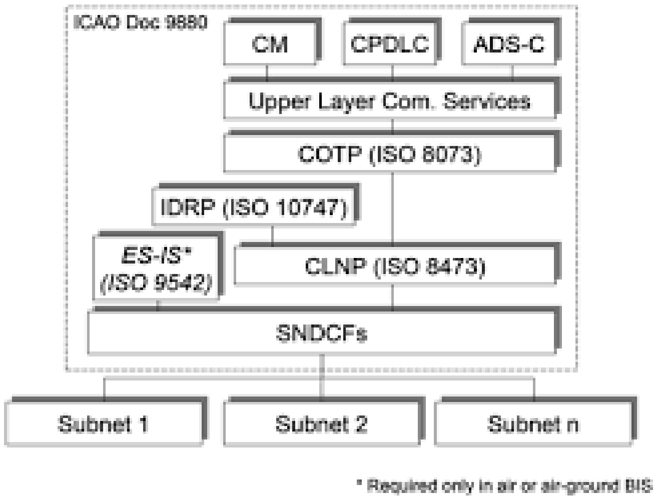


Figure 5: ATN/OSI protocol stack

ATN description

In parallel of the FANS-1/A deployment, the ICAO defines a network architecture called ATN (Aeronautical Telecommunication Network). This architecture, based on the OSI (*Open Systems Interconnection*) protocols and also called ATN/OSI, covers the uppers layers of the OSI model, from the layer 3 to 7 as illustrated in the Figure 5. It also includes protocol applications, dealing with all kind of air-ground communication needs, from the ATC to the APC communications. The new applications defined in this context are named FANS-2/B.

Towards the ATN/IPS

From the beginning of the 2010s, the ICAO has worked on the evolution of the ATN based on IPv6 (Internet Protocol version 6), called ATN/IPS, in order to facilitate the interconnection between the ATN and all the vendors and its development. It is based on a new ground network infrastructure that will meet the need for new more stringent safety services. It is currently under the ARINC and the ICAO standardization and is foreseen to be fully operational in the next decade. The ATN/IPS is expected to use multiple medium access subnetworks that operate under the protected spectrum allocated by the International Telecommunication Union (ITU) and the ICAO for safety services. It will include current systems such as Inmarsat SwiftBroadBand, Iridium NEXT, possibly VDL mode 2 (VDLm2) and the future L-band Digital Aeronautical Communication System (LDACS), Satcom and the Aeronautical Mobile Airport Communication System (AeroMACS). It should also provide backward compatibility with traditional ACARS ATSC and AOC applications, as well as ATN B2 applications that have been defined, so that these applications remain unchanged.

2.2 Different kind of subnetworks

All networks dedicated to perform airborne-ground transmissions require at least one air-ground subnetwork. At the present time, it exists two approaches: cellular system, for which radio transmissions are directly performed between the transmitter and the receiver, and satellite system for which one or several satellites (in a constellation) are used as relay points between the transmitter and the receiver. The different subnetwork systems used for safety aeronautical communications (namely ATSC and AOC) are described in the following. The properties of these systems are summed up in the table 2.

2.2.1 The Line of sight Subnetworks

In this type of subnetwork, all airborne-ground transmissions are achieved directly between a ground station and an aircraft. These subnetworks are also called cellular networks because each ground station can only transmit within its cell, which is defined by its transmission range. So the network is composed of many ground stations to provide a full coverage of the territory. This is the case for systems that uses VHF channels. There are many constraints for such systems, like for instance the frequency allocation inside each cell. Indeed, two adjacent cells cannot share the same frequency as the signals will likely interfere, resulting in a reception of a jammed signal for both cells. Other constraints are the handover between ground stations, and also the shared capacity between all the users in the area covered by a station. The most notable systems based on direct communication links, that are already used or in development, are presented as follows:

ACARS-VHF subnetwork

The ACARS subnetwork, introduced previously, is the first cellular datalink system to be deployed. It offers a binary throughput up to 2.4 kbps using channels of 25KHz, initially reserved for voice communications in the VHF band. The transmission range is about 200km.

HFDL subnetwork

The HFDL (Hig Frequency Data Link) [Org00] was developed to allow the datalink transmission from and to the aircraft when it is located in remote areas, outside the VHF coverage such as oceanic and deserted areas. Due to the inherent curves of HF signals that follow the Earth curve, this system has a very high transmission range and can offer a global coverage with a small amount of ground stations. The drawback of this solution is the very low offered throughput (from 300 to 1800 bps based on the received Signal-to-Noise (SNR) ratio which is highly affected by weather conditions). Concerning the medium access method, the TDMA (Time Division Multiple Access), with a frame length of 32s is chosen, thus the delay before receiving a packet can exceed a minute.

VDL mode 2

The VDLm2 (VHF Data Link mode 2) [Org01] is the main datalink system deployed in continental areas (particularly in western Europe). It is standardized in 1997 by the ICAO in order to support the development of the ATN. The VDL2 subnetwork is based on an interconnection of ground stations offering a throughput of 31.5 kbps in a coverage of 200km per station. It uses the AVLC protocol (Aviation VHF Link Control) in the link layer, and a CSMA-based (Carrier Sense Multiple Access) protocol for the MAC (Medium Access Control) sublayer.

LDACS

The LDACS (L-band Digital Aeronautical Communication System) [MGS20] is currently in development under the SESAR project in Europe. As mentioned in its name, it will use a L-band frequency (between 1.4GHz and 1.5GHz) with a transmission range equivalent to the VDLm2 system (about 120 nm for better performances). The LDACS is an Orthogonal Frequency-Division Multiplexing-based (OFDM) cellular radio system using the Frequency-division duplexing (FDD) with a 0.5MHz channel grid. It should support data and voice communications such as ATSC and AOC datalink applications for safety-critical services. The expected capacity is up to 1.3 Mbps in the Forward Link and up to 1.04 Mbps in the Return Link. One of the key functions of this new radio system is the seamless handover management between the cells. The LDACS medium access method uses OFDM coding schemes, a technique already used in 4G networks, coupled with TDMA (Time Division Multiple Access) method. The LDACS is foreseen for the 2020s.

AeroMACS

The AeroMACS [BFM13] is a new gatelink system, dedicated to communications between the aircraft and the airport ground end systems. It will allow a high speed broadband communication access to aircraft on the ground, enabling them for instance to download huge files such as updating database or mapping. the AeroMACS is directly based on the IEEE 802.16e Worldwide Interoperability for Microwave Access (WiMAX) standard [Fel10]. It will operate on a dedicated C-band reserved for aeronautical communications.

2.2.2 The Beyond Line of Sight Subnetworks

Satellite communication uses indirect links with satellites that act as a relay point in the airborne/ground communication. A constellation of satellites located in Earth's orbit allows to cover a very large surface, including oceanic areas. There are two satellite providers for ATSC applications that have been certified by the ICAO: Inmarsat and Iridium.

Iridium

The Iridium constellation uses 66 cross-linked satellites plus spares which create a network of global coverage.

Iridium supports Short Burst Data (SBD) service and ACARS. It provides High-availability and low latency. Iridium NEXT replaces all of the 66 satellites with 81 new satellites to increase the data capacity to 100 kbps for 90% of the orbit. As with Iridium, it will have global pole-to-pole coverage. The initial launch of Iridium NEXT satellites is scheduled for 2015. Iridium and Iridium NEXT have worldwide coverage.

Inmarsat

Meanwhile, Inmarsat provides land, maritime, and aviation services with geo-synchronous satellites at an altitude of approximately 22.000 NM. Its coverage is from 80°N to 80°S with no polar coverage. There are 2 variant versions to address ATSC applications:

- Aero H+: with multi-channel voice, 10.5 kbps fax and data, delivered via a high-gain antenna within the spot beams of the Inmarsat-3 satellites and the full footprint of the Inmarsat-4 Atlantic Ocean Region (AOR) satellite at a lower cost per connection.
- SwiftBroadBand (SBB): which supports simultaneous voice and broadband data, with IP data at up to 432 kbps, and IP data streaming on demand at 32, 64, and 128 kbps. This is not yet approved for safety services, but it will be the main satellite services for ATN/IPS proposed by Inmarsat in the future.

System	Capacity	Range/Coverage	Operational	ATN/IPS
VDL2	31.5kbps per station	200km	Yes	Yes
HFDL	1.8 kbps per station	2500 km	Yes	No
LDACS	2.3 Mbps per station	200 km	No (expected 2020)	Yes
AeroMACS	30Mbps per station	short range	No (expected 2020)	Yes
Iridium	2.4 kbps per aircraft	global	Yes	No
Iridium Next	100 kbps in total	global	Yes	Yes
Inmarsat H+	100 kbps in total	latitude $< 80°$	Yes	No
Inmarsat SBB	432kbps total	latitude < 80 °	No	Yes

Table 2: Summary of the characteristics of air-ground datalink subnetworks

3 Manuscript content

In this chapter, we described the context of the thesis: the future of safety aeronautical communications. The rest of the manuscript is divided into four chapters.

In the first chapter, the concept of the aeronautical networks namely the ACARS and the ATN/OSI are described in details. We highlight the network functions in these particular networks. Then, the new ATN/IPS is introduced with all the questions raised by its development.

The second chapter deals with the problem of the IP mobility in the ATN/IPS. After identifying the existing solutions to handle the network mobility for mobile devices in IP networks, we propose as a first contribution a global mobility solution for aircraft. The performances of our proposal are assessed in simulation with the OMNeT++ software, and compared to a standard IP mobility solution.

In the third chapter, we study the perspectives of the multilink feature offered by the ATN/IPS. We propose a method based on probe packets to assess the quality of the different air/ground links that is independent from the information coming from the link access layer. To assess the performances of our proposal, we implement it in the SAPIENT framework, a dedicated aeronautical simulated framework in OMNeT++. We then demonstrate the performances of three estimation techniques using the probe delays.

The fourth and final chapter of the manuscript is a conclusion of our work. All the contributions we made so far are recalled, and further work that should be carried out are discussed.

Chapter 1

Aeronautical networks for air safety application services

Contents

Introduction

In the 1980s, the civil aviation industry adopted datalink communications in order to improve the efficiency of the communication between the pilot and ATC centers, in a context of the voice channel saturation. This new type of communication needs a ground network to transmit packets to the right destination. Due to the specific safety constraints in civil aviation, it decided to develop from scratch their private ground network. ACARS network was firstly created in 1978 and later in 2000+, ATN/OSI network was standardised and used in Europe.

1 Existing aeronautical networks

The very particular nature of aeronautical communications forces the civil aviation to opt for a proprietary ground network infrastructure. In this part, a detailed description of the characteristics of both networks is given.

1.1 The ACARS network

1.1.1 Presentation of ground network entities

Entities description

The term ACARS refers to the entire datalink communication system, from air to ground systems, consisting of equipment on board and on the ground. There is also a service provider, whose role is to route messages between two end systems, generally an aircraft and a ground end system. The architecture of the ACARS system is composed of 4 entities, namely: the aircraft, the air/ground network, the Datalink Service Provider (DSP) and the User network.

the aircraft: it is equipped with ACARS end systems that are linked to a router. The router is in charge of routing the messages through the air ground subnetwork.

the air/ground network: it allows to connect the aircraft to a DSP network through different subnetworks. Each subnetwork proposes a specific radio link. Currently, there are 4 types of radio links: VDL2, VHF mode A, Satcom and HFDL.

the Datalink service provider (DSP) network: it is composed of 4 entities:

- *ACARS processor:* manages the air/ground communication for aircraft via the A618 protocol. It also routes the messages between aircraft and ground end systems, by converting them with the A620 format, and vice versa.

- *VHF management system (VMS)*: this entity is directly connected with the VHF ground stations. it is in charge of managing the ground stations and maintaining a connectivity between the aircraft, the stations and the DSP.
- *ATC server*: it is responsible for ATC uplink routing and for the interconnection with other DSPs. The uplink routing function is performed with a tracking table. For each registered aircraft, it memorises the available subnetworks allowing a communication with the aircraft. This information is retrieved in the Media Advisory label (SA label) sent by the aircraft, and it is shared among all the DSPs. When the available subnetwork belongs to another DSP, it must route the ATC messages to the corresponding DSP, in order to grant a high level of integrity. In addition, a Message Assurance Service is ensured via the sending of a transmission report to the ATC center.
- *Host processor (HP)*: It is the interface between the User network (generally an airline) and the ACARS processor. This link can be either an X.25 or an IP link. It also runs the A620 protocol to ensure a ground to ground communication with the User networks.

the user network (usually airline network) : Airline companies use ACARS communications to operate their aircraft via AOC applications that are run in host end systems. For that, they must install a 620 gateway (also called Front End processor (FEP)) that connects the AOC applications to the DSP network. The routing function of the FEP is to route downlink messages to the AOC application and uplink messages to the DSP networks. In addition, messages going through the FEP are either formatted to ARING 620 format or unformatted.

The ACARS network infrastructure is depicted in the Figure 1.1.

1.1.2 The current network deployment

the providers

Currently, the ACARS service is provided by two mains companies: ARINC and SITA that are able to ensure a global air/ground network coverage, through ARINC ”Globalink” service and SITA ”Aircom” services.

- ARINC Globalink: is a air/ground network composed of 3 ACARS processors based in Annapolis, in China and in Thailand. Annapolis is the only one providing all the subnetworks including VHF and VDL mode 2 except in Asia, Satcom and HF. Airlines can subscribe to one or several services to have a global coverage with ARINC provider.
- SITA Aircom is only composed of 2 ACARS processors based in Singapore and Montreal, which is just used as a backup. Both provide VHF/VDL mode 2 and Satcom services.

Other providers have deployed VHF subnetworks in Japon and Brazil, that are connected to SITA network to provide a global coverage. Concerning the Satcom service, there are 2 main providers: Inmarsat with geo-stationary satellites and Iridium with low Earth orbit (LEO) satellites. ARINC and SITA provide the 2 options.

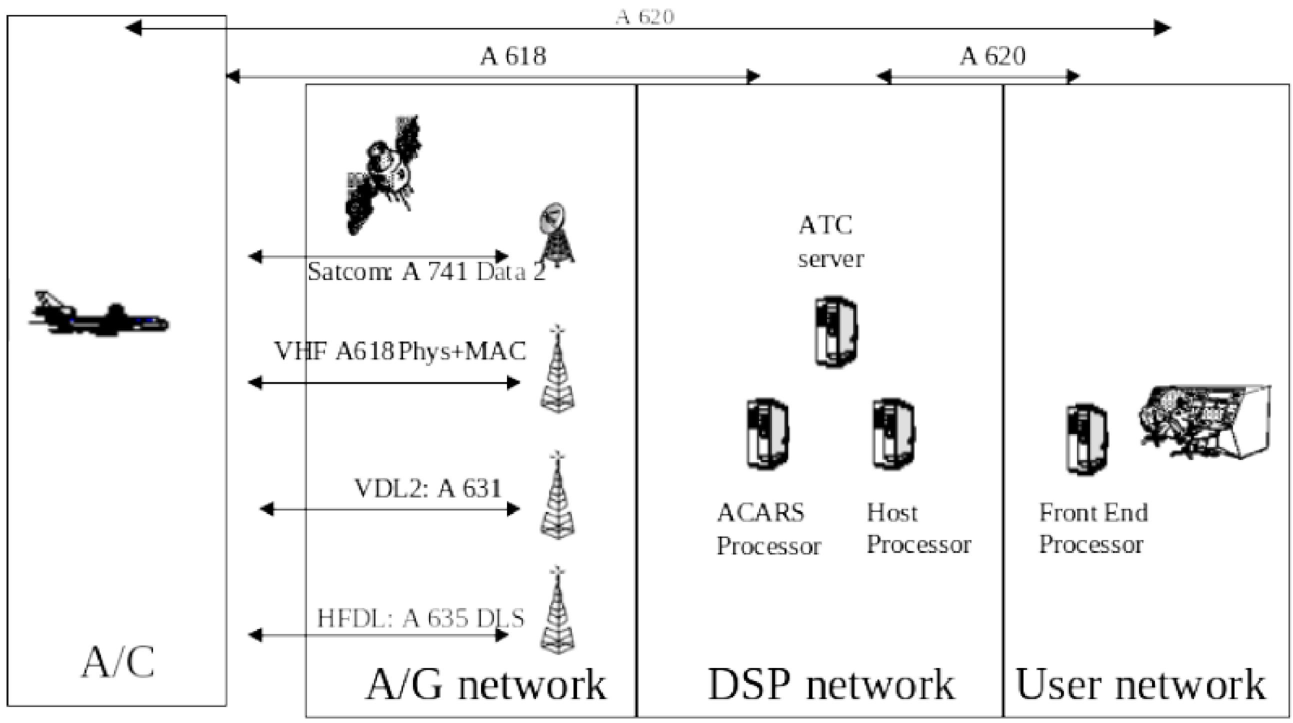


Figure 1.1: ACARS network infrastructure

1.1.3 Functions of ACARS router

Router presentation

An onboard ACARS router is accountable for three main functions: interfacing with applications, routing Uplink messages from ground end-systems and routing Downlink messages to ground end-systems.

- *Interfacing*: a dedicated file transfer protocol is used for ACARS applications. There are different protocols adapted to the communication bus used onboard. For instance, the ATSU (Air Traffic Service Unit) runs the ARINC 619 protocol, while the ACR (Avionics Communications Router) runs the APOTA/TFTP protocol. Both routers equip Airbus's aircraft.

- *Uplink routing*: each message contains a label or a tuple label/sub-label. When receiving an uplink message from a subnetwork, the router uses a routing table to find the destination application corresponding to the label. If the destination cannot be found in the table, the router sends a downlink message "QX" to the sender. The message is then transmitted to the destination using a transfer file protocol mentioned above. If this transmission fails, a "HX" message is sent to the ground source end-system to inform that the message cannot reached the final destination.

- *Downlink routing*: each downlink ACARS message is composed of:

  - a source ID

- a label (B0) or a tuple label/sub-label (H1/M1) to identify the message
- a priority
- a routing policy
- a time to live
- a core message.

Each downlink message is buffered in the ACARS router. A priority is attributed to each application (ATSC prior to AOC applications for instance). The ACARS router then prioritises the processing of the messages that have a higher priority level. If the time spent in the queue by a message exceeds its time to live, it is deleted. In addition, an acknowledgement is sent to the source application when the message is transmitted via the A618 protocol to a DSP.

Routing policy

The routing policies are predefined in the ACARS router. They allow to establish different forwarding rules for each type of applications. On new advanced routers (such as the ACR), they are dynamic in the sense that they are defined per geographical area. A routing policy is composed of:

- a list of subnetworks ranked by preference
- a flag NextOnBusy (NOB): a True value means that if the first subnetwork of the list is currently busy, the message can be transmitted via the second subnetwork of the list. A False value means that the message is transmitted on the first available and idle subnetwork.

The ACARS router needs some information from the subnetworks to route the messages. Each subnetwork must tell whether its status is connected or not and busy or idle. Also, each VHF subnetwork specifies to which provider (like ARINC Europe or SITA Europe for instance) it is connected to. The router is then able to evaluate for each message in the queue, whether it can be transmitted and the subnetwork to use based on its routing policy. When the subnetwork fails to transmit a message, it sends a notification to the router which declares its status as no connected. Let's take an example to better understand the routing policy mechanism. Supposed there are 4 messages in the queue with the routing policy behind:

- msg1: priority 1, Pref_list= 1.Satcom, 2.VHF ARINC NOB = True
- msg2: priority 2, Pref_list= 1.HF, 2.VHF SITA NOB = False
- msg3: priority 3, Pref_list= 1.Satcom, 2.HF, 3.VHF SITA, NOB=True
- msg4: priority 4, Pref_list= 1.VHF SITA, 2.Satcom, NOB = False

Supposed the status of the different subnetworks is the following:

- Status: Satcom = No Connected, VHF= Connected Idle SITA, HF= Busy

The router then processes the messages as follows:

- msg1: waiting
- msg2: waiting
- msg3: transmitted via VHF because the two previous subnetwork in the preference list are not connected or busy and the NOB is True.
- msg4: waiting because the msg3 is being transmitted via the VHF channel, so it is no more idle.

On the ACR, up to 15 different policies can be set up and can be redefined per geographical area.

Signaling

The ACARS router also needs to send some information to the rest of the network. These information are described in the protocol A618-6, issue 7. It first establishes the connection with the ACARS processor via a control label Q0, which replies with a label _DEL. Then the router sends the Media Advisory (SA label) to inform the ground entities about its subnetworks.

1.2 The ATN/OSI network

The FANS committee recommended in 1983 new applications to provide better air traffic management services in the context of air traffic growth. In 1989, another committee was in charge of implementing a new concept CNS/ATM (Communication Navigation Surveillance/ Air Traffic Management) to ensure the efficiency and the safety of the air traffic control. To handle an increasing of both growth of data and air traffic, a replacement of the ACARS network was necessary. The ATN Panel (ATNP) was created in 1993 to develop the SARPs (Standards and Recommended Practices) for the ATN network that is necessary to support the CNS/ATM concept. Its role is to interconnect the aircraft, ATC center, airlines networks and service provider networks together to offer a safer and more efficient end-to-end service than the ACARS network. To avoid extra cost, the ATN is based on standard communication protocols that can also connect existing networks. The PETAL 2 and the Link 2000+ programs succeed to implement the ATN network in Europe. While in the United States, the project was cancelled due to the extra costs and delays.

1.2.1 Presentation of ATN/OSI ground network

The ATN network is very particular in the sense that it addresses very specific constraints. Firstly it must run dynamic routing protocols to manage the aircraft mobility in the internetwork. Also, due to the low capacity of radio links, the protocol overhead must be kept as minimum as possible. The last point concerns the critical data exchange. The ATN network must ensure reliability, safety and a certain level of quality of service.

Architecture

The ATN network is composed of the following components:

- ATN router or Intermediate System (IS): supports the lower layers up to the network layer. Its role is to route the messages inside the ATN network.
- End Systems (ES): provides the communication service to applications by implementing the 7 layers of the ISO model.
- Boundary Intermediate System (BIS): is an ATN router that connects networks from different organizations (or routing domain).
- the different air/ground and ground networks are connected to the ATN network by the ATN routers. VDL mode 2 is the first air/ground subnetwork for the ATN network. Is is foreseen in the future to include SATCOM over the ATN network.

We define the following terms that are used in the ATN network:

- Routing Domain: A set of end systems and intermediate systems that operate according to the same routing procedures and that is wholly contained within the single administrative domain.
- Routing Area: A routing sub domain comprising one or more intermediate systems (ISs) and optionally one or more end systems.

Following this definition, we also define the different roles of the ISs in the network as followed:

- Level1 IS: an IS that exchanges routing information inside its routing area, between all Level1 ISs in its routing domain by IS-IS protocol such as ?
- Level2 IS: an IS that exchanges routing information between all Level2 ISs in its routing domain by IS-IS protocol. Level2 IS implements Level2 subnetwork and has information for routing area level routing.
- BIS: an IS that exchanges routing information between BIS by the Inter-Domain Routing Protocol (IDRP).

1.2.2 Communication protocols

The ATN layer 3 and 4 are based on the OSI stack model. The complete ATN-OSI stack is displayed in the Figure 1.2. The routing function performed at the layer 3 is our main focus. Routing information are exchanged via the Connectionless Network (CLNP) protocols. 3 protocols are used depending on the type of systems involved:

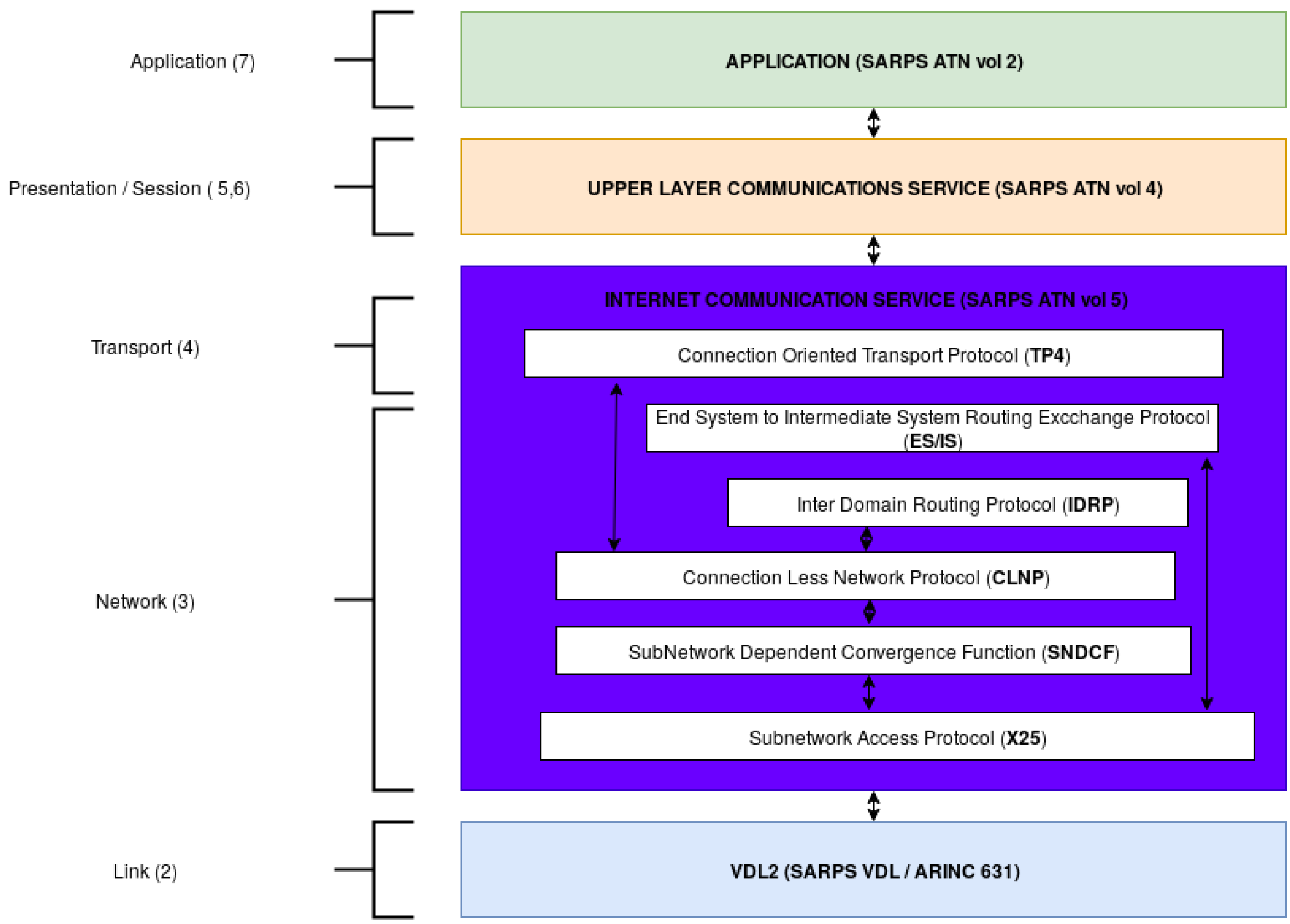


Figure 1.2: ATN protocol stack

- ES-/IS protocol: is used to discover its neighborhood. ESs discovers adjacent ISs and other ESs in their subnetwork, while ISs uses this protocol to identify adjacent ESs in the subnetwork.
- IS-IS protocol: is used to spread the IS routing information to the other IS belonging to the same routing area. Each IS is then able to build shortest routes to each system in the network based on these information. To reduce the signaling, only IS on the same level are allowed to exchanged routing information.
- IDRP protocol: is to used to exchange routing domain information between BISs.

2 The new ATN/IPS

The IPS (Internet Protocol (v6) Suite) for Aeronautical Safety Services will participate in the modernization of the ATM that is expected to widely use datalink communications in order to enhance performance-based operations. The choice of using IPv6 instead of IPv4 is to meet the demands of the Internet growth in the future as more and more devices need to be connected to Internet. IPv6 will provide a larger address space compared to IPv4, and also additional features such as the stateless address auto-configuration.

2.1 General description

The ATN/IPS is intended to provide an efficient and robust network infrastructure for safety aeronautical communications, namely ATS and AOC communications. It is currently under development and is foreseen to be the next generation of the aeronautical network that will support the interconnection of all the stakeholders. The choice of the IP protocol is motivated by the large variety of existing products and vendors, its high level of maturity and its continuous development led by other industries. The deployment of the ATN/IPS is expected by the end of this decade. An overview of the network is presented in the Figure 1.3. Currently in the standardization phase, the ICAO 9896 document [Org09] specifies some initial considerations for the IPS architecture, which include the connection-oriented Transmission Control Protocol (TCP) and extensions per RFC 793 [rfc81] and RFC 1323 [BBJ92], connectionless User Datagram Protocol (UDP) per RFC 768 [rfc80], and general Internet Protocol inter-networking based on IPv6 per RFC 2460 [HD98]. On top of that, there is an IP adaptation layer which helps the current applications to use the TCP and UDP without any necessary modifications.

The Future Communication Infrastructure (FCI) for the ATN/IPS will be composed of different subnetworks:

- An aircraft which is considered as a mobile subnetwork hosting airborne end-systems (A-E). It can be either seen as a mobile node or a mobile network at the IP level. It includes an airborne router (A-R) responsible for the link selection and the management of the inter-technology handovers, and also airborne radios (AR) providing the communication over air/ground links.

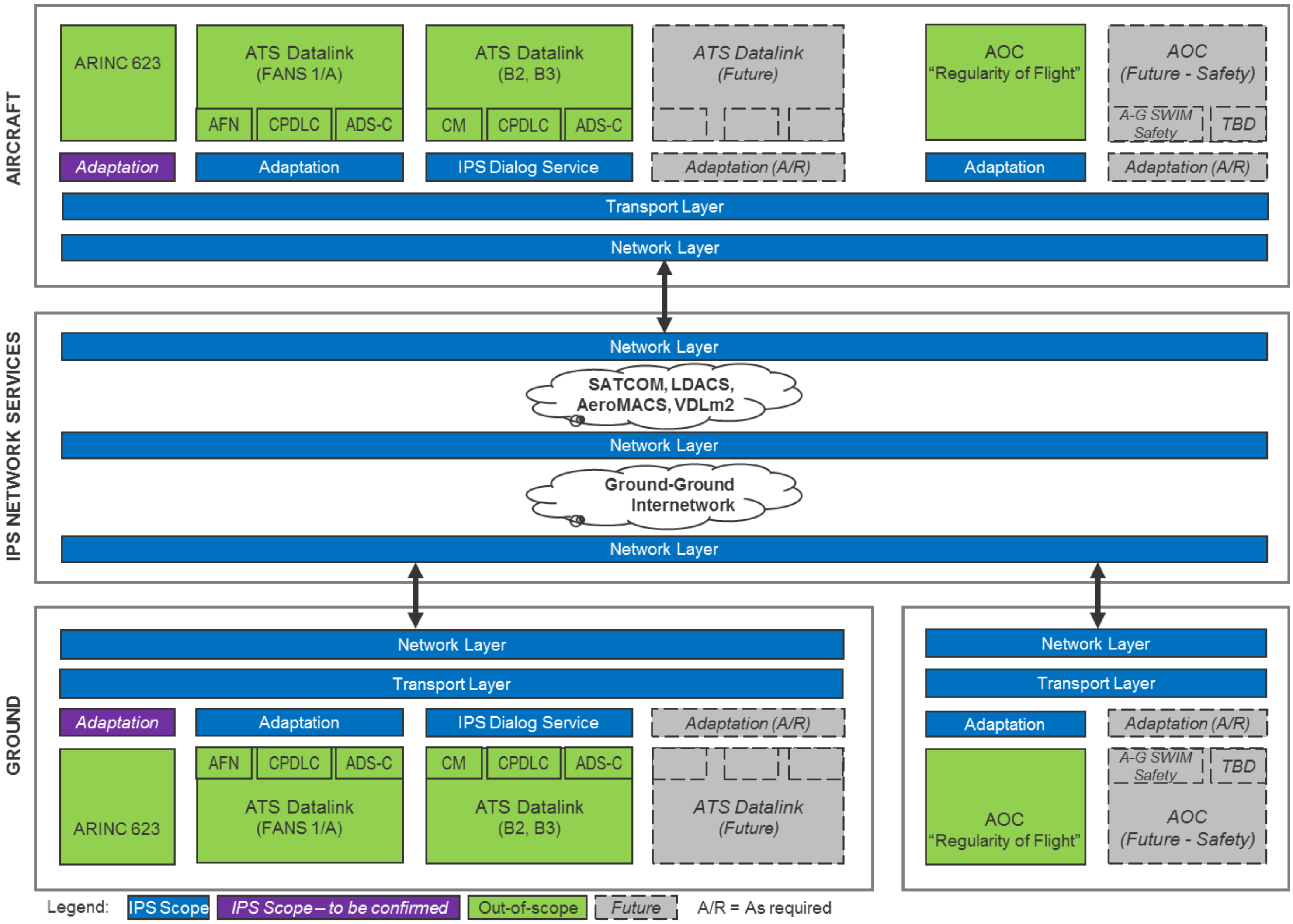


Figure 1.3: the ATN/IPS overview

Source: ARINC 658

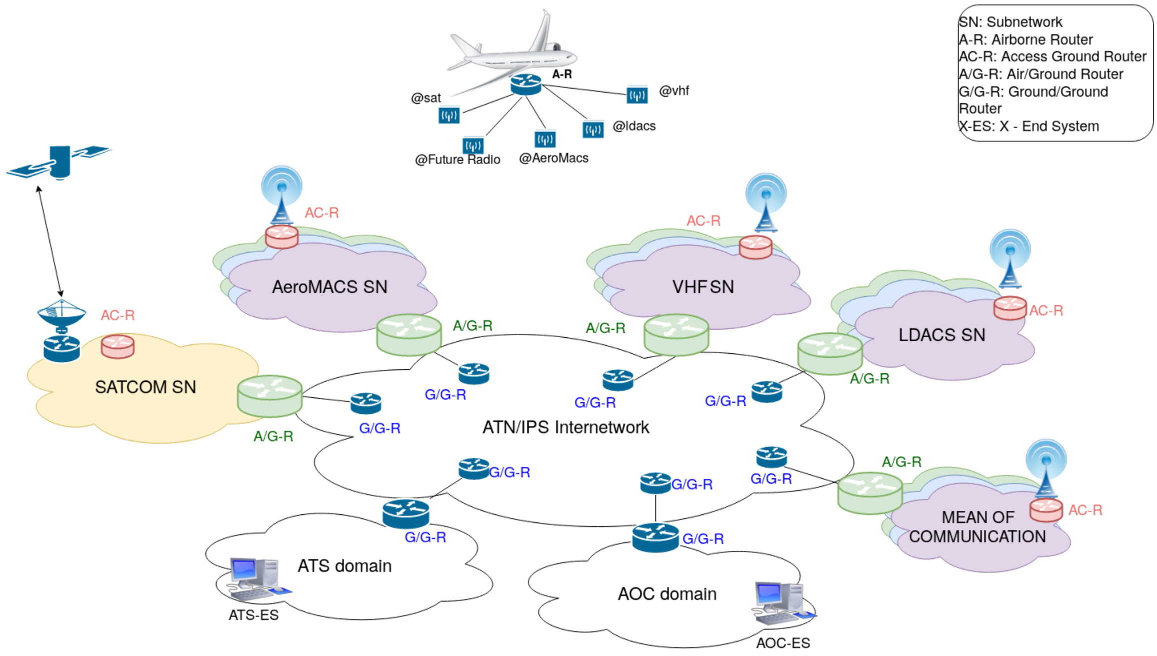


Figure 1.4: the FCI

- Access Networks, which refer to the subnetwork providing the air/ground link between the aircraft and the ground systems. They include specific radio communication means to reach the aircraft (such as VDLm2, LDACS, SATCOM, and future communication means), an Access Ground router (AC-R) which is the last hop router towards the aircraft, and an Air/Ground router (A/G-R) to connect the access network to the ground ATN/IPS internetwork. Access networks belong to Datalink Service Providers (DSP), whose aim is to provide a connectivity to the aircraft. Hence, several access networks may be grouped into the same administrative domain.

- Applicative Service Providers are ground end-systems communicating with airborne end systems ensuring a certain service. Some examples of Applicative Service Provider are the ATC Centre and Air Navigation Service Provider (ANSP) whose role are to manage the air traffic, or the AOC centre which are dedicated to handle airlines operations.

- the ground ATN/IPS Internetwork is the core network of the ATN/IPS. It maintains a connection between all the different subnetworks.

The FCI, shown in the Figure 1.4, will be the interconnection of all these subnetworks and hence securing an IP end-to-end communication between all the aeronautical stakeholders.

2.2 Major issues in the ATN/IPS

Switching toward IP communications brings out many challenges and new problems to solve in terms of IP mobility, addressing, multilink, quality-of-service, security, etc. More details on these topics can be found in [Org09] and the ARINC 658 document [AEE20], produced by the AEEC (Airlines Electronic Engineering Committee).

2.2.1 Addressing

We focus here on the addressing problem on board due to the multiple wireless network interface an aircraft has. In IPv6, each network interface allowing a node to be connected configures a global unicast IPv6 address. This address directly belongs to the service provider in charge of providing the connection through this interface. Indeed, the global IPv6 address is built from a prefix allocated by the service provider. This process can be either automatic or configured for each aircraft. So the aircraft may have multiple global IPv6 addresses with different prefixes, as the airline company may choose different service providers. There are different options:

- Having assigned multiple prefixes to simplify the multihoming configuration.
- Having assigned multiple IPv6 addresses that will introduce complexity to route the packets to the aircraft.
- Having a single global IPv6 address per aircraft, as the unique identifier used in ACARS and ATN/OSI network, with network mobility/multihoming management, to simplify the deployment on board.

This concern will be decided by the authorities and therefore we will not address this challenge in this thesis. Thereafter, we will assume the last model of addressing as it is the one that matches the most with the previous ATN/OSI network.

2.2.2 IP mobility

The aeronautical telecommunication network is a specific network in which global mobility needs to be handled. Indeed, the aircraft must be reachable from at least one service provider subnetwork, this one can change during the flight depending on the type of contract subscribed by the aircraft's company. An IP mobility protocol thus has to be implemented in order to manage the aircraft reachability to the ATN/IPS. It will highly depend on the way addresses are set on board, as seen above in the section 2.2.1. In this thesis, we made a proposal to solve the IP mobility challenge the the ATN/IPS. Our proposal will be defined and assessed regarding the expected performances of such a protocol.

2.2.3 Multilink

As said previously, the heterogeneous environment in which aircraft evolve may offer multiple choices in terms of the communication means to use. Also, in order to benefit from this typical environment, an aircraft must be able to use multiple links at the same time to increase availability and performances. That is what we call multilink capability. It means that the communication session at the application or transport layer must be maintained even if the communication is performed via different links. However, when talking about multilink, one can think about using the secondary links as the redundant link in order to improve robustness. But in our case study, multilink is only used to improve performances in terms of bandwidth. In other words, packets from different types of application may use different links that are best suited for their communication needs. For instance packets with low delay requirement may be transmitted over slower links. One feature that must be required is the multi-homing to allow the aircraft to be simultaneously reachable from multiple air/ground subnetworks. In addition, in this heterogeneous environment, the quality of the primary link in use may degrade due to network congestion or bad signal quality, thus the choice of the best air ground link may change and need to be updated. Therefore, a dynamic decision management algorithm has to be developed and implemented for that purpose in order to minimize loss of availability and delay of end-to-end communication. In this thesis, we made an original proposal to help the multilink algorithm gathering information for the decision. Our solution is independent from the multiple link layer technologies.

2.2.4 Security

The new airborne router will be based on IP protocols, thus resulting in new security risks that must be clearly identified and mitigated. The high-level security objectives have been listed in the *ARINC 658* document, in terms of integrity, confidentiality and accessibility. All data send over air/ground subnetworks must be completely secure, and depending on the level of security required, several layers of security (from the physical to the application layer) may be defined. This thesis, focused in the network layer, do not propose any mechanism to ensure that data exchanged over the network layer are secure, as it is not excluded that other security mechanism will be sufficient. In addition, adding too many layers of security may become a burden and degrade the overall end-to-end communication performances.

Conclusion

This chapter gives an overview of the different types of network for safety aeronautical communications. Existing network infrastructures cannot cope with the growth of global air traffic and the demand of new types of datalink applications. Therefore all the civil aviation stakeholders agree on developing a new network infrastructure based on the IP technology, known as the ATN/IPS, to meet the future communication needs. Indeed, this technology has the advantage of being used worldwide and also robust so that it will ease the development of future aeronautical communications systems. This thesis proposes innovative solutions for the IP mobility and the multilink challenges in this new aeronautical network infrastructure.

Chapter 2

Aircraft network mobility in the ATN/IPS

Contents

Introduction

In the new ATN/IPS, presented in the chapter 1, one of the two major topics we address in this thesis concerns the IP mobility. Indeed, the aircraft evolves in an heterogeneous environment composed of many different link technologies, that are managed by different datalink service providers (DSP). As soon as the aircraft's company subscribes to different providers, a mobility protocol is therefore necessary to manage seamless handovers and to ensure a service continuity for on-going safety applications. Unlike vehicles or smartphones which often move inside a service provider domain, the aircraft may be reachable from different datalink service providers and different link media along the flight. It is particularly the case for inter-continental flights like transatlantic ones, where the aircraft will move from a satellite access to a ground access medium that belongs to a different service provider.

Moreover, the very specific constraints of aeronautical network with global mobility, complexity onboard and very scarce radio resources must be taken into consideration while defining a mobility protocol for such an environment. After studying the different mobility solutions for other type of mobile devices, we end up with our contribution for solving the aircraft network mobility in the future ATN/IPS. The results have been published in [AAN19].

In this chapter, we first explain the different types of mobility an aircraft may experience during a flight. Then, we review the current state of the art to solve node mobility in IP networks and see which one can be suitable for handling aircraft mobility. Finally, we propose a global solution for managing all the mobility scenarios in the future ATN/IPS and assess its performances in simulation with a framework we specially developed. This framework reuses modules from the INET framework, an open-source communication networks simulation package for OMNeT++, that simulates a lot of wired and wireless protocols from the physical to the application layers.

1 Aircraft network mobility: definition

In this part is presented the different types of mobility, also called handovers, that are likely to happen in the ATN/IPS, and their impact on aeronautical communications. Indeed, the ATN/IPS will be composed of many different entities providing IP connectivity to the aircraft. A handover occurs as soon as the aircraft switches from one wireless access point to another one. As the ATN/IPS will integrate more and more link technologies, handovers will inevitably occur and the aircraft will perform different types of handovers to handle such events. In the following, we first present the wireless access network and then explain what is a handover and its properties. Then we will discuss the properties of the mobility protocol in order to ensure session continuity for critical aeronautical applications.

1.1 Wireless access network

1.1.1 Definition

Wireless access networks are composed of two entities: ground base stations and mobile wireless network interfaces. The groud base station is the point of attachment for wireless hosts inside its coverage and allows them to establish a radio link. Each base station is linked to an access router that is able to forward packets for the hosts in the internetwork. The wireless access network is operated by a service provider.

On the other side, the wireless network interface is attached to the onboard router and allows the aircraft to communicate with ground base stations. Each network interface is identified by a unique Media Access Control (MAC) address. The format of this address is 48 bit long, and it is used as source and destination of packets (also called frame) exchanged via the radio link between the aircraft and ground base stations. The MAC address is also known as a link-layer address.

1.1.2 Base station handover

A property of wireless communication is that it relies on the range between the host and the base station. Due to the mobility of the host, the radio link between the two entities may be broken and a new one has to be established so that the host remains reachable. This phenomenon is called handover. A handover can be initiated by the mobile host or the network: either one of them decides when and to which base station a handover must be performed. Here, we will only focus on mobile initiated handover. The procedure for this handover consists in three phases, as follows: handover information, handover decision, handover execution.

The mobile host generally receives beacons that are sent periodically by base stations. The beacons include network information such as the address of the base station, the label of the service provider, quality information regarding the access network, etc. The first step consists for the mobile host to collect these information. Then, the handover decision phase consists in comparing the collected information and, based on certain metrics (preference, contract, signal strength, pricing, etc...), deciding the next base station. The third phase is the execution of the previous decision, meaning that the mobile host may advertise the target base station of its willingness to establish a new radio link. The mobile host then negotiates with the target base station basic capabilities, eventually followed by authentication procedures in case a new wireless network is selected. As soon as the registration is completed, the new radio link between the target base station and the mobile host is successfully established, implying that data can be transmitted and received using this new link. The radio link with the previous base station may be interrupted by the mobile host or the previous base station, depending on the link technology.

1.2 Types of handover

1.2.1 Mobility defined by link access technology

Handovers can be define by the link technology of the previous and the next network access point the mobile node uses. There are respectively called horizontal and vertical handover.

Horizontal handover

A horizontal handover involves two network access points that share the same link technology. For instance, it may concern cellular access networks such as the VDLm2, or the future LDACS. The Figure 2.1 describes a horizontal handover performed by an aircraft from access point #A to #B.

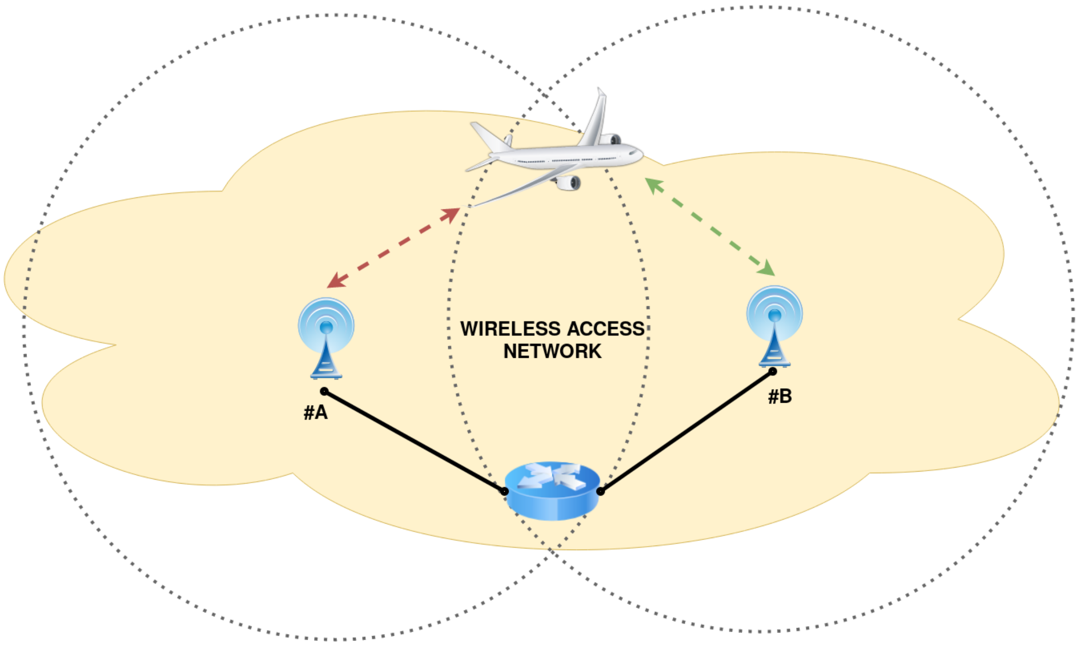


Figure 2.1: Intra-domain horizontal handover

Vertical handover

A vertical handover involves two network access points that share different link technology. In the future ATN/IPS, several link technologies are foreseen, and there will be more and more link technologies as the ATN/IPS has been chosen to ease their integration. A practical case of vertical handover, described in the Figure 2.2, occurs in transatlantic flights when the aircraft exits the continental area and has to switch from a wireless ground access network #A to a satellite access network #B to remain reachable.

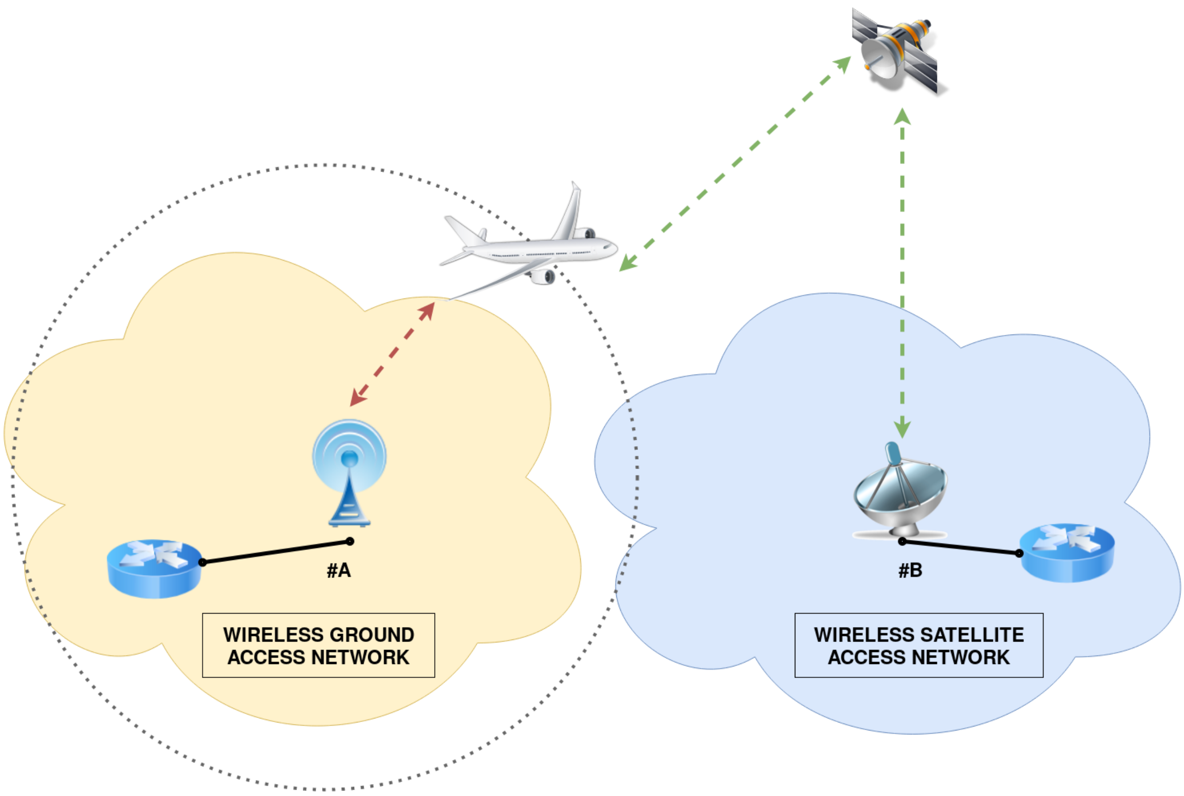


Figure 2.2: Inter-domain vertical handover

1.2.2 Mobility defined by administrative domain

Handover can also be defined by the degree of network mobility and can be distinguish between intra-domain and inter-domain handover.

Intra-domain handover

An intra-domain handover occurs when a mobile node stays in the same IP domain after performing a handover. Such handovers are typical in continental areas, which are covered by several network access points to provide a seamless connectivity in these regions. The next network access point #B belongs to the previous network access point's (#A) service provider as shown in the Figure 2.1. Usually, both network access points use the same technology, but in the aeronautical environment where there will be more and more link technology, it is not excluded that a service provider may offer more that one type of connectivity to the aircraft.

Inter-domain handover

An inter-domain handover occurs when a mobile node moves to another IP domain after performing the handover. The most common case is when we consider a vertical handover, as illustrated in the Figure 2.2, where the two link technologies belong to different service providers such as Inmarsat for the satellite link and former ARINC for the VDLm2 link. However, it is possible that some airlines want to subscribe to different service providers for the same link technology, depending on geographical areas for instance. In this case, horizontal handover is also considered as an inter-domain handover.

1.3 Session continuity

Session continuity is a mandatory feature for critical aeronautical applications in the ATN/IPS. Indeed, breaking the sessions after each handover leads to packet loss and more delay due to the re-establishment of the connection, and thus it is no more possible to meet the requirements for critical applications mentioned in the Table 1.

How to provide session continuity

In IP networks, an application session is bound to a global IP address, thus a change of this IP address will break the session. In order to provide session continuity in the ATN/IPS, the global IP address that is used must remain unchanged after a handover occurs.

Seamless handover

All these handovers discussed above may happen during a flight. However, their impacts at the network layer differ from one to another and thus a mobility protocol has to be implemented in order to provide seamless handover to the aircraft, hence session continuity to aircraft applications. Aircraft performing an intra-domain handover does not change its global unicast IPv6 address because it will remain in the same IP domain after the handover. If it is a horizontal handover, the session continuity will be ensured by the link layer technology that has to associate the aircraft to the new access point seamlessly. For a vertical handover in the same IP domain, the mobility protocol must ensure multihoming so that on-going session can smoothly switch to the new network interface. For this purpose, all the network interfaces managed by the same administrative IP domain must have the same IP address.

Aircraft performing an inter-domain handover does change its global unicast IPv6 as it will switch to a new IP domain and thus have to obtain a new IPv6 address. In this case, for both horizontal and vertical handovers, in order to ensure session continuity, the mobility protocol must bind the previous and the next global unicast IPv6 address of the aircraft together, so that only one of them is used permanently. The table 2.1 summarizes the functions of the mobility protocol for each handover scenario.

Types	Horizontal	Vertical
Intra-domain	No management	Multihoming + IP Mobility
Inter-domain	IP Mobility	IP Mobility

Table 2.1: Handover scenarios

2 State of the art

The problem of IP mobility is known for a while with the introduction of laptops. Nowadays, with the emergence of wireless mobile devices such as smartphones, cars, trains, IoT devices, and so on, the need to remain connected to the Internet increases. However, the IP mobility problem evolves from one area to another as they do not have the same mobility pattern and the same constraints. In this part, we first highlight the differences between the aeronautical network environment and the other areas and explain what are the important requirements a mobility protocol has to fulfill in this domain. Then, a review of the existing IP mobility protocols is given with their advantages and drawbacks, based on the requirements previously identified.

2.1 Specific requirements in aeronautical networks

2.1.1 Particularities of aeronautical network

Characteristics of aeronautical communication compared to other types of IP mobile communication

Mobile phones communications, defined in 3rd Generation Partnership Project (3GPP), also need an IP mobility protocol as mentioned in [IGM07]. Compared to aeronautical communications, mobile phones are just mobile hosts while aircraft can be seen as a mobile network. Mobile phones are also limited in their movement, and the principal handover they are facing is the horizontal handover inside the same 3GPP network, which is often performed at the Link layer. Some work related to mobile networks have been initiated in Monet (Mobile Network) in the early 2000s. T.Ernts and al in [EBO$^+$02] propose an adaptation to MIPv6 (Mobile IPv6) for nodes in a mobile network. The Car2Car communications environment may deal with several end-systems located inside the car, and hence can be seen as a mobile network. However, the Car2Car protocol stack is not only made of an IP stack. It also considers a proprietary Car2Car protocol stack to manage safety communications [BFA07]. Besides, the degree of car's mobility is limited to continental areas and thus there is not many choices in terms of link technology.

To sum up, the particularities within aeronautical communications, compared to other areas, are: the presence of several link technologies, a high degree of mobility that may imply long delays due to routing over large distances, and also a need to ensure high availability and security for critical applications.

2.1.2 Protocol requirements to support IP mobility in the ATN/IPS

We have seen previously that the aeronautical communication domain is very specific compared to others. Therefore, before choosing or defining a mobility protocol, we define a set of requirements that must be satisfied by the candidate protocols. The list of requirements is as follows:

1. **Session continuity**: is fulfilled as soon as a permanent IP address is used by upper layer protocols, that is not changed after a handover.

2. **Handover management**: the kind of IP handover the protocol helps to manage among the ones presented in the Table 2.1.

3. **Multihoming**: if the aircraft is reachable from more than one link medium, it must be able to route data simultaneously over these multiple links, taking into consideration the state of the link and the type of application.

4. **End-to-end delay**: the communication delay between the aircraft and the ground system should be as minimal as possible to meet the Quality of Service (QoS) constraint. These constrains have been defined in [EtFAAF06]. The Table 2.2 sums up the most stringent requirements from this document. The RTT represents the number of message exchanges, 1 meaning that 2 messages have been exchanged.

5. **Scalability**: the mobility protocol should mitigate its impact on the global routing infrastructure.

6. **Protocol overhead**: represents the header for each data packet induced by the mobility protocol. It must be as small as possible in order to consume the minimum bandwidth.

7. **Protocol signalling**: represents the amount of mobility protocol packets exchanged. It must be as low as possible, at least concerning the packets transmitted over radio links to not degrade their performances.

8. **Routing udpate**: in case a new interface is available for communication, or an interface switches toward an other radio link, the new routing path from and to the aircraft must be detected and usable as fast as possible for packet forwarding.

9. **Deployment**: the impact of the protocol in terms of infrastructure and cost for a future deployment.

Service	Delay (in s)	RTT
ACL	3.0	2
ACM	3.0	1
COTRAC	5.0	3.5
FLTPLAN	30	9

Table 2.2: Service requirements from the COCR

2.2 Protocols to support IP mobility

Different approaches have been conducted to handle the network mobility problem. These approaches are either based on the network, the transport layer or the application layer. The two last approaches are tight to a host-based solution. Transport layer based solution involves kernel space implementation, thus increasing the cost of deployment and maintenance, as mentioned in [KYVL19]. Concerning application layer based solution such as [CCL11] [SKTY06], SLM (Session Layer Mobility) [LLIS99], ROCKS (Reliable Sockets) [ZM02], TESLA (Timed Efficient Stream Loss-Tolerant Authentication) [SSB03], SMSL(Session-based Mobile Socket Layer) [KGdSM14], they are bound to a certain type of protocols such as the Session Initiation Protocol (SIP) and cannot be generalized, as mentioned in [KYVL19]. An approach like this is not suitable for the aeronautical safety environment due to the high development and standardization cost it will induce on the avionics side. Therefore, this survey boils down to the study of network layer based solutions. They are often classified into two categories: host-based and network-based solutions.

2.2.1 Host based protocols

In a host-based solution, the mobile host is responsible for managing its network mobility. This kind of solution reduces the complexity in the network infrastructure by pushing it to the end-systems. Host-based solutions are performed at layers on top of the network layer.

Host Identity Protocol (HIP)

The HIP [MJHN08] proposes a radical approach in dealing with the network mobility problem. Indeed, the problem comes from the unique address used for both identification at the transport layer and localization at the network layer. HIP introduces a shim layer between the network and the transport layer in order to split the locator-identifier dilemma. Inside this shim layer, it introduces a new namespace on top of the IP address namespace, in which a globally unique identifier is used to identify a mobile host. The upper layers use this identifier, instead of the IP address of the host, thus allowing the debinding of the IP address. This approach is also used in LIN6 (Location Independent Network Architecture for IPv6) [MFOO03], SHIMv6 and other network-based protocols.

HIP uses Host Identity Tags (HITs) as identifiers. They are generated from the public key used in IPsec, thus the HIT is unique and can only be used by the node with the corresponding private key. To establish an HIP communication, a message exchange is initiated between the two nodes (shown in the Figure 2.4), to share the HITs and the IP addresses they want to use. In case of a mobile node, if it moves to a new location and get a new IP address, it informs the corresponding node of the new IP address via the HIP UPDATE packet containing the locator parameter. Then both HIP modules update their state to map the new IP address to the corresponding HIT, as specified in [NVAH08]. The multihoming feature is also managed as an HIT can be mapped to several IP

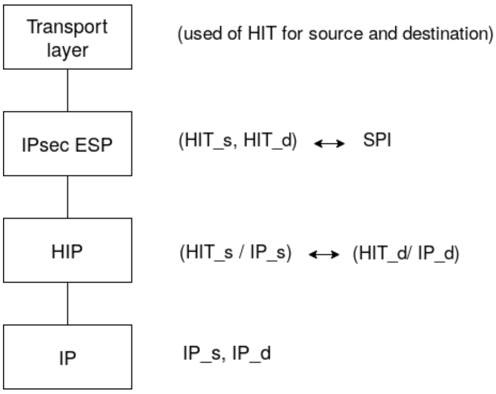


Figure 2.3: Host Identity Protocol implementation

A HIT tag is created for both source (HIT_s) and destination (HIT_d), derived from IPsec public key.
The Security Parameters Index (SPI) uniquely identifies an IPsec Encapsulated Security Payload (ESP) security association.
IP_s and IP_d refer to source and destination IP address respectively.

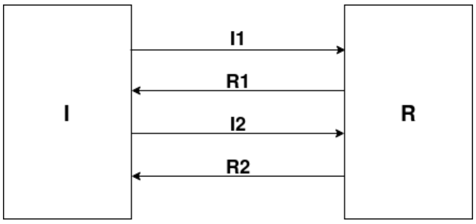


Figure 2.4: HIP session establishment

addresses. The Figure 2.3 shows how the HIP is implemented in an IP stack.

HIP uses a Rendezvous Servers (RVS) to handle the mobile nodes [EL08]. It allows the mobile node to advertise its new IP address to not only its current corresponding nodes but also other future nodes that would like to establish a communication and are unaware of its location. Mobile nodes perform registration with a RVS and then update their entries in the Domain Name System (DNS) to include the address of this RVS. A correspondent node willing to contact the mobile node performs a DNS lookup based on the mobile node's domain name and then obtains the address of the RVS. The contact initiation from the correspondent node is sent to the RVS from where it can be forwarded by the RVS to the current location of the mobile node, as shown in the Figure 2.5, where the initiator *I* is the correspondent node and the the responder *R* is the mobile node. The RVS, noticing that the packet *I1* is not for itself forwards it to the registered mobile node's IP address. Then the mobile node directly responds to the correspondent node to establish the HIP session, and the procedure follows the one described in the Figure 2.4.

Analysis

Session continuity: The upper layer protocols are bound to the HIT, which does not depend on the IP address location of the mobile node. Hence, the impact of a new IP address configured after a handover is limited to the update at the HIP layer.

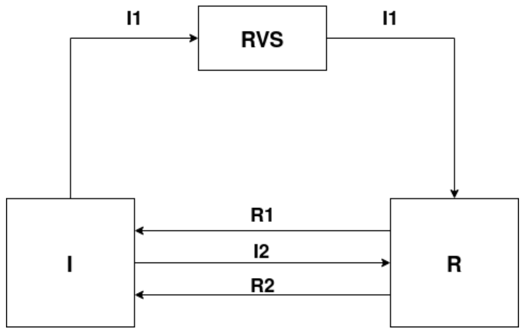


Figure 2.5: HIP session establishment with a rendezvous server.

Handover management: The HIP performs similarly for any handover scenarios.

Multihoming: the Multihoming feature is described in [HVA17]. Firstly, it was only focused on fault tolerance, meaning that another path was used only if the preferred path was no more available. Simultaneous usage of different interfaces, for load-balancing for instance, is performed using multiple Security Associations (SA), one for each load-balanced path, thus involving a lot of signalling.

End-to-end delay: The data traffic follows the shortest path between the two peer nodes. Hence the delay is minimized.

Scalability: Scalability issue may arise in the RVS as it has to manage the binding (HIT, IP address) for the mobile nodes. Concerning the routing infrastructure, there is no change with HIP, as only end-systems have to use the new identifier HIT.

Protocol overhead: the HIP uses the IPsec Transport mode to exchange the data between two peers. Therefore, the overhead induced is due to IPsec header (12 bytes), and is present in each data packet.

Protocol signalling: To establish a HIP sessions between two peers, 4 messages are exchanged, taking 2 round trip times. Whereas when updating the location of a mobile node, 3 messages are exchanged, thus taking 1.5 round trip times. The signalling is performed for each correspondent node.

Routing update: is performed when a mobile node changes its location and obtains a new IP address. Therefore, the delay involved is equal to the time it takes to establish the mapping update (HIT, new IP address) between the peer nodes. In case the mobile node is involves in many communication with several correspondent nodes, it has to update all its binding with all these nodes.

Deployment: the HIP needs a RVS, and also a modification on all end-systems protocol stacks as it is a host-based solution, which can be very costly.

The HIP fulfills all the requirements but its major flaw is that it must be implemented in the aircraft, inducing a lot of signalling when a handover has to be performed.

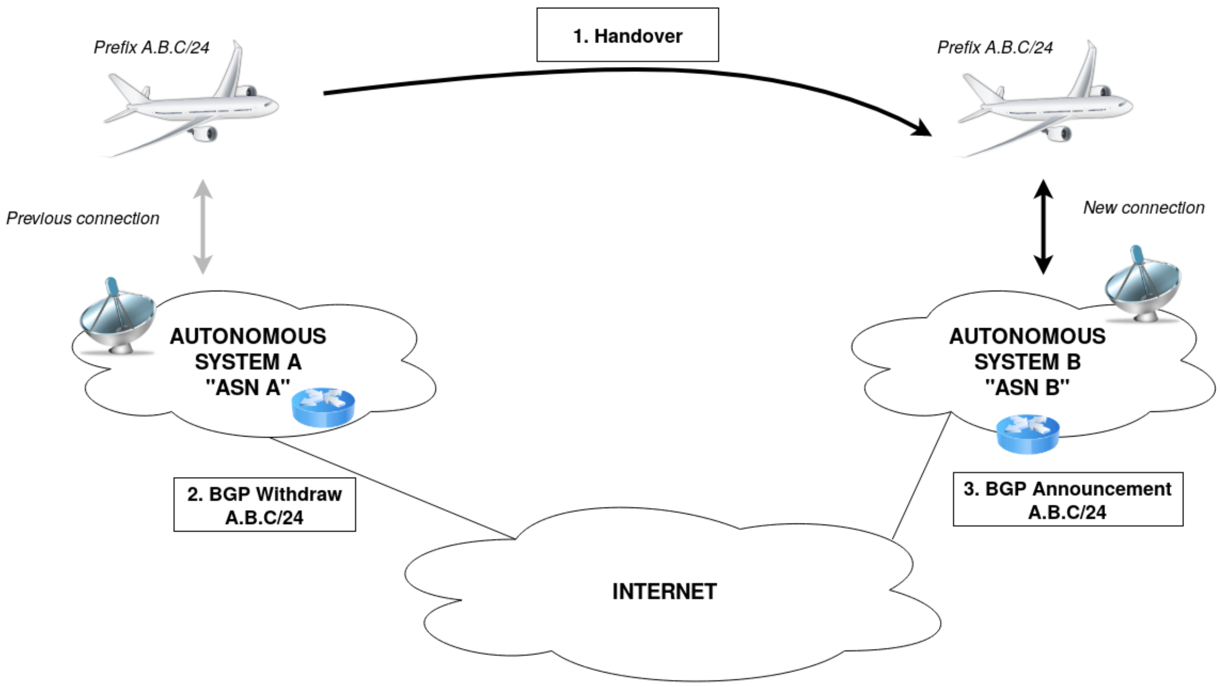


Figure 2.6: BGP mobility management

2.2.2 Network based protocols

In network-based solution, one or several entities are introduced in the network infrastructure to deal with the node mobility. The main advantage of this approach is the transparency towards the mobile host, which do not need any modifications inside their protocol stack. The different solutions are detailed in the following.

Border gateway Protocol (BGP)

Whereas routing protocols have not been designed to solve mobility in IP networks, they can somehow help establishing new routes in a mobile environment. The well known Border Gateway Protocol (BGP) [rfc89] is the main protocol on which the Internet relies on. In the BGP, a routing domain, usually controlled by a single administrator domain, is called an Autonomous System (AS). It is identified with an Autonomous System Number (ASN). They exchange via the BGP routing information to specify the path toward destination prefixes. Routing information is sent to neighboring routers, which in turns update their routing tables and forward the routing information to other routers based on some policies defined between the ASs.

BGP has already been used for aeronautical passenger communications in order to grant them an Internet access (IPv4) via satellite links. The solution is presented in [Dul06]. The mobility management of this solution is described in the Figure 2.6.

The aircraft is given a /24 prefix. Ground stations are autonomous systems using a BGP router/speaker to announce the destination they can reach. Whenever an aircraft is attached to a ground station, the latter updates its routing table and announces the aircraft prefix. When a handover occurs, the previous ground station (belonging to *ASN A* in the figure 2.6) withdraws the aircraft prefix and the new ground station (in *ASN B*), after the aircraft establishes the new link, starts to announce the aircraft prefix. After all the ASs receive this information and update the new route toward the aircraft, packets at its destination will be forwarded through the *ASN B*.

In the BGP, to prevent advertising flapping routes that are frequently announced and withdrawed, a mechanism called route dampening is performed. It helps BGP routers to not accept nor advertise these kind of routes. In the deployed network considered, an aircraft handovers once every 4 to 8 hours, thus causing no dampening based on [TSD+20]. Nevertheless, in the new ATN/IPS network topology, where not only satellite access networks are considered but also several terrestrial access networks, route dampening with BGP may become an issue, as more frequent handovers may occur. A proposal to use BGP for the ATN/IPS is currently in a draft version [TSD+20].

Analysis

Session Continuity: The aircraft is identified by its unique prefix (for instance an IPv4 /24 prefix in [Dul06]), independent from its point of access, from which on-board end-systems configure their address. In consequence, upper layer sessions do not break after a handover. The current ground station is in charge of announcing the aircraft prefix to the rest of the internetwork.

Handover management: The BGP is an external routing protocol, thus it can only helps with the inter-domain handover.

Multihoming: BGP multihoming is a well known technique in the Internet, by using for instance destination-based routing decision when the router is multihomed.

End-to-end delay: The packets follow the optimal path to reach the destination, therefore the end-to-end delay is minimized.

Scalability: When a handover occurs, the previous BGP router and the current one have to update their routing information and inform of either a route withdrawal or a route announcement. Therefore, the scalability is linear with respect to the number of mobile nodes performing handovers.

Protocol overhead: Packets from and to the aircraft do not use any encapsulation methods, and BGP do not add any specific header, therefore the size of the packets remain unchanged.

Protocol signalling: Considering the deployment of the solution in [PTS+19], the only information exchanged on the radio link when a handover occurs is the aircraft identity and prefix, via a HELLO message.

Routing Update: Assuming that the ATN network has its own BGP routing, which is composed of a small number of ASs compared to the Internet, the routing update is not really a problem. However, all the BGP routers must update their route toward the new aircraft location.

Deployment: No additional entity nor specific implementation is required except the IPv6 protocol stack.

The BGP offers some possibilities regarding IP mobility problem and multihoming but it is very limited as it was not designed for these purposes. Indeed, the scalability may be a huge problem if the number of providers and subnetwork accesses rise, as it will trigger a multitude of possible handovers, thus triggering a lot of routing information being exchanged.

Mobile IPv6 and its extensions

In the context of the IPv6, the Internet Engineering Task Force (IETF) has developed an extension to IPv6 to deal with the mobile nodes (MNs) attachment to the network, which is Mobile IPv6 (MIPv6) [PAJ04]. Besides, in [BA08], the author has already performed a simulation assessment of the MIPv6 in an aeronautical environment for safety applications. He assessed the performances of the MIPv6 in terms of the traffic signalling evaluated different flight scenarios and measured the handover delay for each of these scenarios.

The MN is identified with 2 IPv6 addresses: a Home Address (HoA) and a Care-of-Address (CoA). The first one identifies the node in its home network and the second one allows to locate the node when it moves to a foreign network. The association of the 2 addresses is realized by a ground entity in the home network called the Home Agent (HA). Each time a MN attaches to a foreign network, it performs a binding association between its new CoA and its HoA by sending a Binding Update (BU) message to its Home Agent, which replies with a Binding Acknowledgement (BA) message. The HA then creates a bi-directional tunnel to forward traffic to the new location of the MN. A correspondent node (CN) communicates with the mobile node by using its HoA. Therefore, when a MN performs a handover to a new IP network, it remains transparent for its CNs. The procedure is summarized in the Figure 2.7.

This mechanism allows session continuity as all packets coming from CNs are captured by the Home Agent and then forwarded to MNs. However, it introduces a triangular routing because packets sent by the mobile node are forwarded by standard IP routes. To solve this issue, MIPv6 allows MNs to perform route optimization (RO) with their CNs. Route Optimization is carried out after a binding association. The MN creates a secure bi-directional tunnel with its CNs so that packets are exchanged directly through this tunnel.

Whereas the MIPv6 can provide session continuity during a handover phase, its mechanism is not well adapted in specific environments such as in aviation, or for some specific applications which require very constraint requirements. For instance, when the aircraft is far from its home agent, it may have an impact on the handover delay and thus introduce a long period during which the mobile node is unreachable. In the following, some enhancements to the MIPv6 are described in order to mitigate these issues.

- **Hierarchical Mobile IPv6 (HMIPv6)**: the HMIPv6 is introduced in [CSBM05] as an extension to MIPv6. It helps reducing the signalling traffic during the handover phase for local mobility case thanks to a new entity called the mobility anchor point (MAP). It works as a local HA for a MN. HMIPv6 separates the global network into different MAP domains, each one controlled by one or several MAPs (shown in the Figure 2.8). A MAP domain is different from a network domain. The HMIPv6 introduces 2 addresses to manage the local mobility

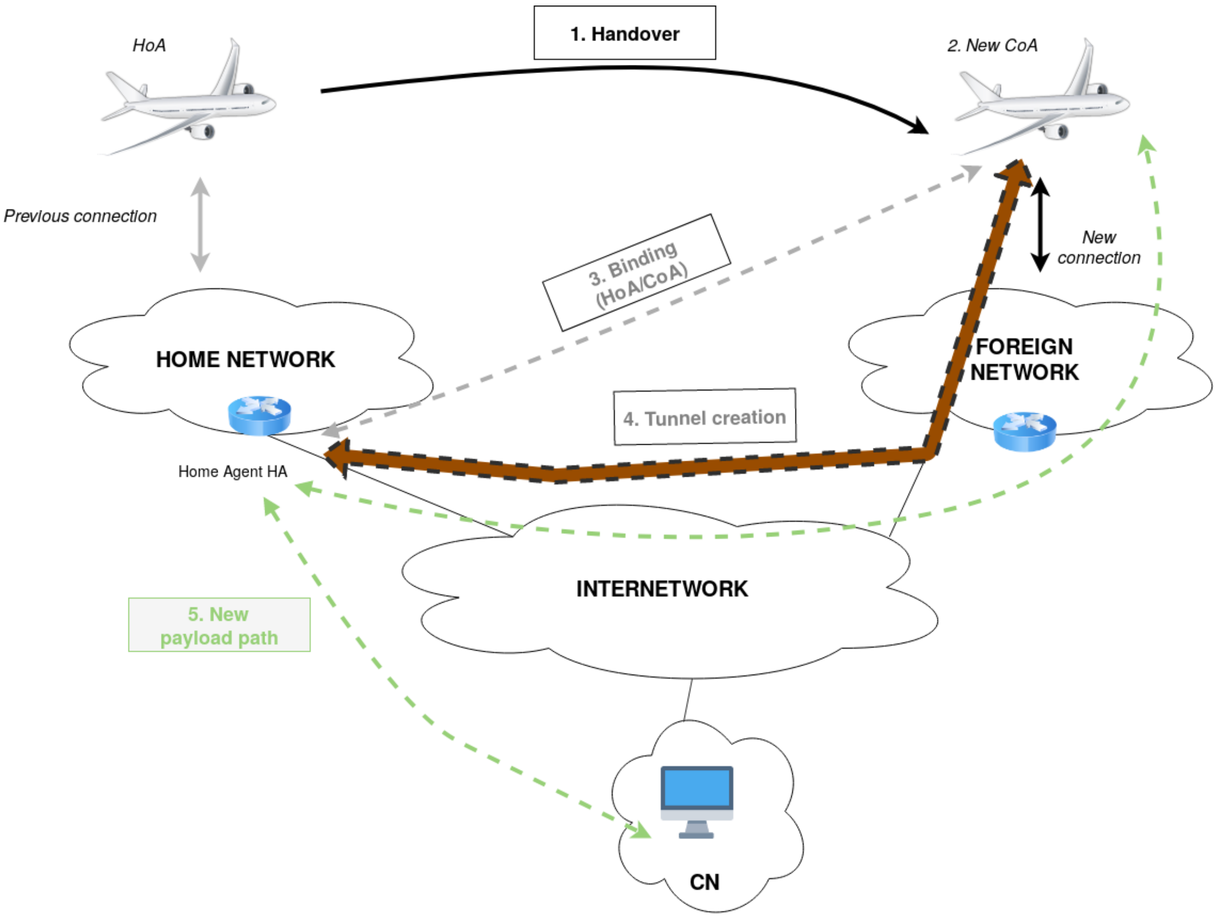


Figure 2.7: Mobile IPv6 handover management

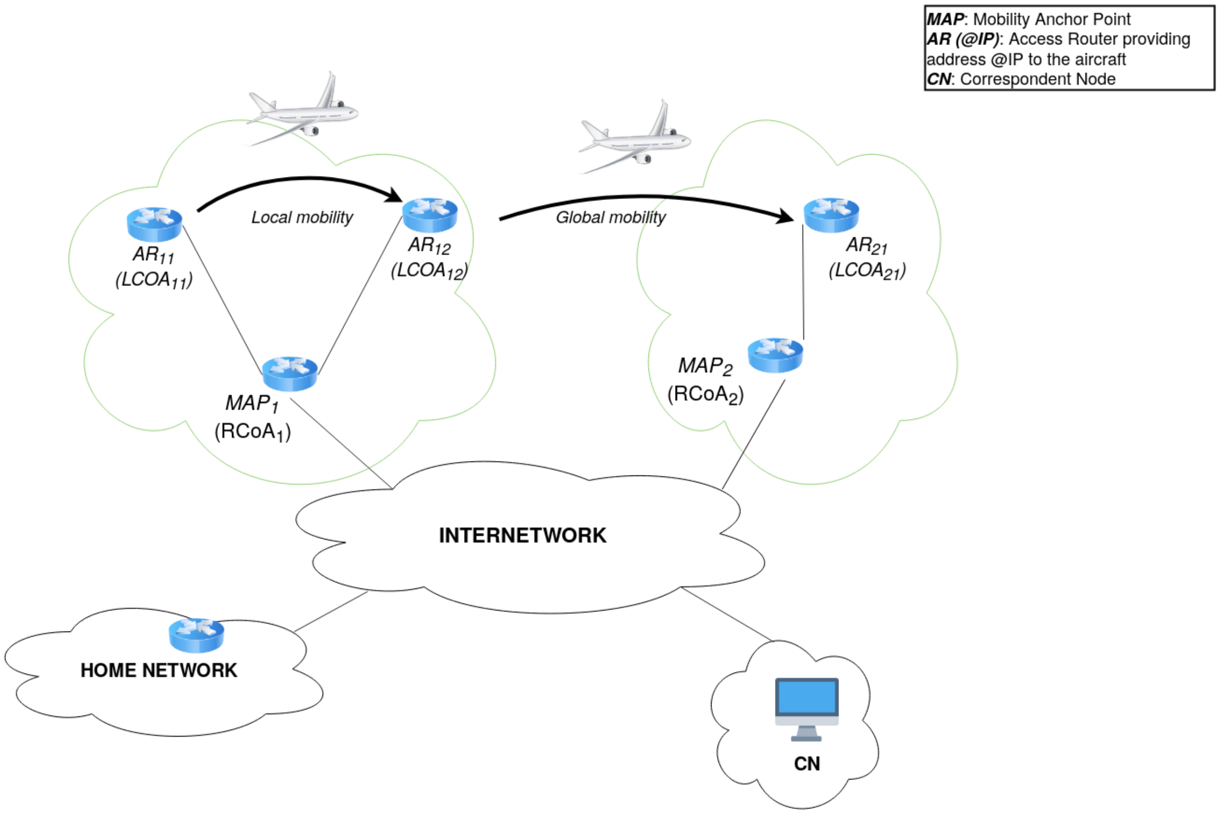


Figure 2.8: HMIPv6 handover scenarios

of a node: the Regional Care-of-address (RCoA) and the Local Care-of-address (LCoA). The first one (RCoA) is used to realize the binding with the HA and the CN, if the route optimization procedure is triggered. The MN obtains a new RCoA whenever it moves to another MAP domain and attaches to a new MAP. Meanwhile, the second one (LCoA) is used as a binding with the RCoA in the MAP domain. This process allows the MAP to forward packets destined to a MN in its current location through the tunnel created between the RCoA and the LCoA. Besides, the HMIPv6 makes the local mobility in a MAP domain transparent to the HA and the CN as the RCoA is not updated.

In consequence, the HMIPv6 is more suitable for local mobility but presents some drawbacks in dealing with global mobility because MNs need to get 2 different global IP addresses instead of only one with the MIPv6, and also need to inform both the MAP and the HA of its new LCoA and RCoA respectively.

- **Proxy Mobile IPv6 (PMIPv6)**: The previous solutions, whereas they are classified as a network-based solution, involve the mobile node in the mobility signalling procedure. In the PMIPv6 [CLP+08], the node mobility is entirely managed by the ground infrastructure.

  Like the HMIPv6, the PMIPv6 provides mobility support within a domain called a PMIP domain. As long as the MN moves within the domain, the network has to track the location of the MN, which keeps its global IP address. The MN is authenticated with the help of a AAA (Authentication, Authorization, Accounting/Auditing) server. PMIPv6 introduces 2 new entities to manage the node mobility: the mobile access gateway (MAG) and the local mobility anchor (LMA). The MAG realizes the mobility-related signalling on behalf of the MN using its access links, after the MN has passed the authorization process run by the AAA server. It is responsible for detecting the movement of the nodes in the domain and for executing binding registration with the corresponding LMA. The LMA manages the routes for all mobile nodes in the domain. More information about the whole process are developed in [LL15] [CLP+08] [BCM12].

In consequence, the PMIPv6 is more suitable than the HMIPv6 in an environment where the radio resource is very limited, such as the aeronautical network environment. Also, the RFC 7864 [Ber16] allows multihoming features by using multiple MAGs at the same time to forward packets from and to the mobile node.

Analysis

Session continuity: The mobile node maintains a persistent IP address (the Home Address HoA) given by its Home Agent from its Home network. So, any correspondent node which wants to send packets to the mobile node, uses the mobile node's HoA address, and thus independently of the mobile node's location. Packets are captured by the Home Agent and tunneled to the mobile node's location.

Handover management: originally the MIPv6 only supports inter-domain handover, whereas the extensions HMIPv6 and PMIPv6 are more focused on intra-domain handover. A combination of MIPv6 and either HMIPv6 or PMIPv6 is suitable for managing any kind of handovers.

Multihoming: Multihoming is not natively handled by the MIPv6. One way to enable this feature is to register several care-of-addresses for a single home address, as highlighted in [WTD+09]. Moreover, the RFC 6089 [MTK+11] specifies a policy exchange protocol that can be used to setup forwarding rules for certain traffic flows, by binding them to a care-of address without affecting other flows using the same home address. A traffic selector makes its decision based on different parameters such as: the source and destination IP addresses, transport protocol number, the source and destination port numbers or other fields in IP and higher-layer headers. A mobile node can thus decide of the policy to adopt and inform its home agent via a Flow Identification Mobility option, inserted in the binding message. This allows for simultaneously routing traffic flows over different interfaces, on the routing path from the mobile node to the home agent and the return path.

End-to-end delay: the MIPv6 induces non-optimal routing because of the Home Agent, which intercepts all the packets. So depending on the distance between the mobile node and its home agent, it may have a huge impact on the end-to-end delay.

Scalability: Mobile IP protocols involve new ground network entities, called Home agent, to track the mobile node location. The Home Agent updates the mobile node's binding cache in its database, but there is no additional route information exchanged with the rest of the inter-network as the mobile node belongs topologically to the home network.

Protocol overhead: Mobile IP protocols is based on tunnel creation with the mobile node. Therefore, each payload packet has an overhead of a full IP header. The only exception is with the PMIPv6, where the tunnel is created between two ground entities and therefore has no impact regarding the mobile node.

Protocol signalling: The MN updates its Care-of-Address in its Home Agent binding cache, by sending a Binding Update message. This message is acknowledged via a Binding Acknowledgment message and the new tunnel is created.

Routing update: After a handover is performed, the Home Agent must wait for the Binding Update message to know the new location of the mobile node so that it can forward the data packets to the new care-of-address.

Deployment: The MN needs to implement the MIPv6 protocol in order to be able to manage their location inside the ATN/IPS network. Besides, a specific entity called Home Agent need to be deployed. The extension HMIPv6 and PMIPv6 also need a new proxy inside the domain to manage node local mobility. Noted that PMIPv6 doesn't implement new functions on the mobile side.

The MIPv6 offers a inter-domain mobility solution whereas the HMIPv6 and the PMIPv6 extensions are dedicated to improve the intra-domain handover cases. A solution combining the MIPv6 with either the PMIPv6 may be considered, such as in [GK16] [McP16], to exploit both protocols' strengths, but it also involves a specific implementation on the avionic side, such as the HIP solution.

Locator/Identifier Separation Protocol (LISP)

Another approach to deal with node mobility is with the LISP [FFML13]. It is a fully network-based solution allowing the mobile node to handover between different administrative IP domains and radio technology. It reuses the same address splitting principal as the HIP, namely the Routing LOCator (RLOC) and the End-system Identifier (EID) namespace. RLOC are globally routable IP addresses used to localize the end-system and route the packets in the network, while EID are fixed addresses dedicated to identify an end host. All the routing functionalities are moved to the ground with the Routing Locator Space (RLOC), and thus it does not require to make any modifications in the end-system, minimizing the implementation cost on the mobile node's side. LISP routers, namely ingress Tunnel Router (iTR) and egress Tunnel Router (eTR), together with a mapping system (MRMS) maintain a mapping cache between the RLOC and the EID addresses, and use the encapsulation/decapsulation method to forward packets to the end-systems. The MRMS is also referred as the control plane, whereas iTR and eTR (also called xTR because usually the router performs both functions) are assimilated as the data plane.

The LISP is based on 2 phases: a registration phase and a routing update phase. These 2 phases are illustrated in the Figure 2.9.

The first phase consists of step 0, 1 and 2. The mobile node (here an aircraft) establishes a link with the access network. It gives its EID (AC_ID) to the ingress Router iTR which informs the Mapping System of a new association

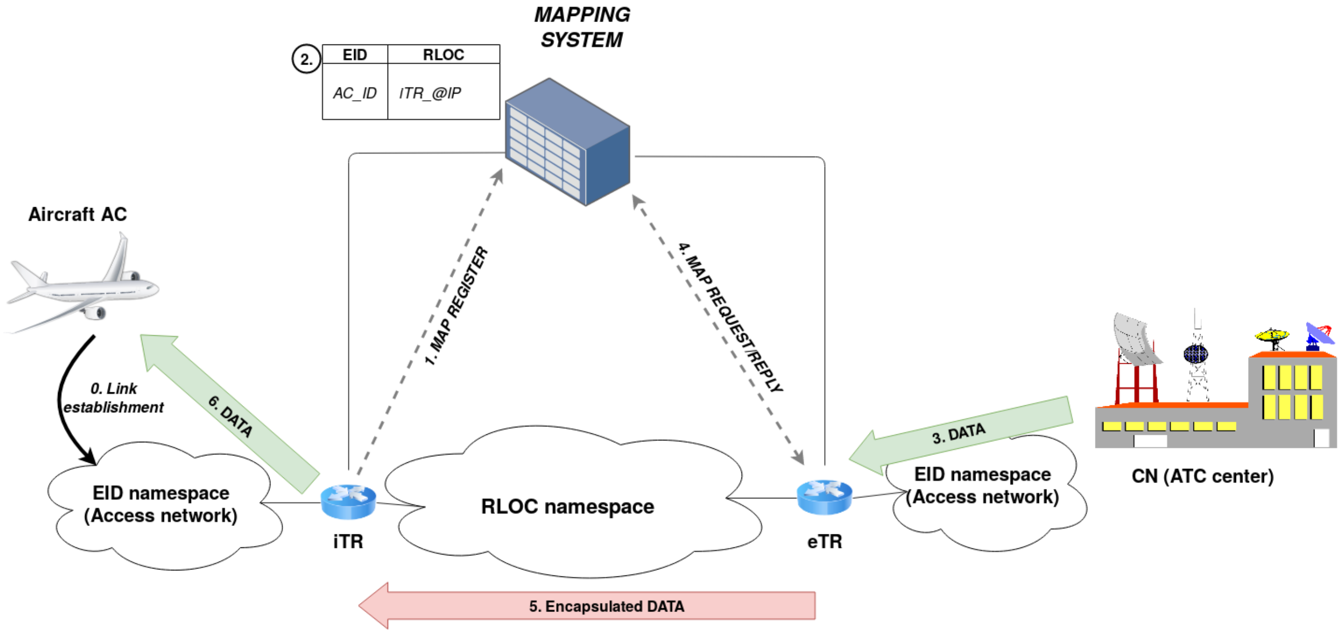


Figure 2.9: LISP mobility management

(AC_ID, iTR_@IP). At this point, the egress Router doesn't know the location of the aircraft. The routing update phase (step 3 and 4) starts only when a packet must be transmitted to the aircraft. The correspondent node CN starts a communication with the aircraft and wants to send a packet to the aircraft's EID address (the procedure to describe how the CN knows this fixed address is outside of the scope). Once the packet reaches the eTR, it asks the mapping system for the RLOC address attached to the aircraft EID with the MAP REQUEST/REPLY exchange. Then after getting the corresponding RLOC address, the eTR encapsulates the original data into an IP packet with source address eTR_@IP and and destination address iTR_@IP (step 5). Then, the packet is decapsulated at the iTR and forwarded to the aircraft EID using standard IP routing (step 6). In [HL16], the authors propose Ground-LISP (G-LISP) which is dedicated for an aeronautical environment.

Analysis

Session Continuity: As soon as end-systems use a different namespace (EID namespace) to communicate, session continuity is fulfilled as the end-systems never see the RLOC address when a mobility event occurs.

Handover management: the RLOC addresses are used to route the packets in the inter-network, whereas the EID address of the end-system is used to route the packets inside the same domain. Therefore the LISP only deals with inter-domain handover.

Multihoming: more than one RLOC addresses can be assigned to an EID, thus packets can be forwarded through multiples paths to reach the mobile node.

End-to-end delay:: The path for the encapsulated packets between the ingress and egress routers follows the one established by standard external routing protocols. Besides, the path to forward data from the end-system to the ingress/egress routers is defined by internal routing protocols. Therefore the end-to-end delay is optimized.

Scalability: Like the HIP, the LISP is based on a mapping system and thus dot not modify the routing table of routers. Scalability issue boils down to the the mapping system, which has to handle the mobile node's EID-to-RLOC association.

Protocol overhead: To reach the RLOC destination, packets are encapsulated into an IP packet, thus implying an extra IP header overhead. However, this has no impact on the radio link, as this encapsulation is performed by the ground ingress router.

Protocol signalling: LISP signalling messages are exchanged between the ingress/egress router and the mapping system. One message is sent from the ingress router to the mapping system each time the ingress router notices an end-system coming or leaving its network domain. A message exchanged is performed between the egress router and the mapping system, when the egress router needs to forward packets to an unknown EID address. In any case, the LISP does not involve the mobile node, assuming that the ingress router obtains its EID from internal routing protocols for instance.

Routing update: The information of the mobile node location (EID-to-RLOC association) remains in the egress' database for a certain time. LISP does not specify how to update the EID-to-RLOC association inside egress routers. So, when a handover occurs, the time it takes to establish the new path is equal to the time it takes the new ingress router to notice the mapping system of the new EID-to-RLOC association, plus the the time it takes the egress router to get the new EID-to-RLOC association.

Deployment: the LISP is a new mobility protocol, therefore 2 news entities need to be deployed : tunnel routers and a mapping system. However, it does not modify the IPv6 stack inside the mobile node.

The major strength of the LISP is that the mobility management is entirely performed on the ground network. However, it only solves the inter-domain handover.

2.2.3 Classification of mobility protocols

The previous section gives an overview of the existing protocols that have been proposed to handle node mobility in IP networks. Here, we provide in the Table 2.3 a summary to help us discuss on the most suitable mobility solution to handle aircraft mobility in the future ATN/IPS network. We classify the solutions in 4 classes, according to their degree of fulfillment between optimal ($\bigoplus$), acceptable ($\oplus$), average($\odot$) and unsupported ($\ominus$).

All of the protocols achieve at least one requirement with limited fulfillment. The main drawback with the HIP is that all the mobile nodes need to implement the protocol, which is very costly in terms of certification. The BGP is not designed to handle mobile node, especially when there are a lot of ASs. Indeed, whenever the aircraft change its point of attachment, all the ASs need to update their route to reach it. The Mobile IP protocols suffer from the fact that it does not provide optimal routing and involves packet encapsulation to transmit the payload. Based on

Protocols	HIP	BGP	MIPv6	PMIPv6/HMIPv6	LISP
Session continuity	$\bigoplus$	$\bigoplus$	$\bigoplus$	$\bigoplus$	$\bigoplus$
Handover management	$\bigoplus$	$\oplus$	$\odot$	$\odot$	$\oplus$
Multihoming	$\odot$	$\odot$	$\bigoplus$	$\oplus$	$\bigoplus$
End-to-end delay	$\bigoplus$	$\bigoplus$	$\ominus$	$\odot$	$\bigoplus$
Scalability	$\odot$	$\ominus$	$\oplus$	$\oplus$	$\oplus$
Protocol overhead	$\oplus$	$\bigoplus$	$\ominus$	$\oplus$	$\oplus$
Protocol signalling	$\odot$	$\ominus$	$\oplus$	$\oplus$	$\bigoplus$
Routing update	$\oplus$	$\odot$	$\oplus$	$\oplus$	$\odot$
Deployment	$\ominus$	$\bigoplus$	$\oplus$	$\oplus$	$\oplus$

Table 2.3: Candidate protocols to fulfill mobility requirements for ATN/IPS network (optimal $\bigoplus$, acceptable $\oplus$, average $\odot$ and non compliant $\ominus$)

the elements provided, the most suited protocol is the LISP. However it does not solve all mobility scenarios as it is not interested in intra-domain handovers. Moreover, the routing update is a real problem as the ingress router only updates the routing location (RLOC) when its cache expires. In a highly dynamic environment, it thus may not convey packets toward the current aircraft location. In the following section, we propose a solution to the problem of the LISP so that it can fulfill all the requirements in the ATN/IPS.

3 Mobility solution for the ATN/IPS

In this section, we aim at providing a global mobility solution able to cover all the handover cases. The ATN/IPS network infrastructure is the one presented in the Figure 1.4. We assume that the access network is composed of several datalink service providers access network, in which they propose either one or several link access technology. Also, each airline may have a contract with one or more datalink service providers. In the case the airline has only one DSP, their aircraft will only perform intra-domain handovers, while on the other case with multiple DSPs' contracts, the aircraft will execute inter-domain handovers. We have seen previously that the LISP is only suitable for inter-domain handover, that is why our idea is to couple the LISP with PMIPv6, an intra-domain handover solution that does not involve neither any signalling on the aircraft side nor extra code implementation on-board. Another possible choice would have considered to combine BGP with the PMIPv6, however, while it allows to minimize the end-to-end delay, the scalability may become a big concern in the ATN/IPS environment where more and more link technologies and subnetwork providers will be included in the future. Firstly, we describe how our solution can be implemented in the ATN/IPS. Then, we illustrate how the registration phase and both intra and inter-domain handovers are executed with our solution.

3.1 Protocol description

3.1.1 General principles

The idea is to take advantages of both protocols in order to propose the best solution to manage the aircraft mobility in the ATN/IPS network. Indeed, the LISP, described in the previous section 2.2.2, provides efficient inter-domain handover management but eludes the problem of intra-domain handover. For instance, the G-LISP (Ground LISP) proposed in [HL16] relies on an internal routing protocol like the Open Shortest Path First (OSPF) protocol to solve the problem. Likewise, the PMIPv6 presents interesting properties for the ATN/IPS such as the absence of implementation on board and the lack of protocol signalling exchange with the aircraft. Nevertheless, it is only capable of managing intra-domain handovers. The solution presented in [GK16] [McP16] solves the issue of inter-domain handover by coupling the PMIPv6 with the MIPv6 protocol. While this approach benefits from using similar protocol signalling messages, the MIPv6 presents many drawbacks in the aeronautical environment such as the additional IP header, due to tunneling, on the radio link, and the inefficient routing path between end-systems.
We show in the following how to achieve the combination of both the LISP and the PMIPv6, and also how our solution can be implemented in the ATN/IPS internetwork shown in the Figure 1.4. In the following and for the rest of the manuscript, our solution is referred as Proxy-LISP (P-LISP).

3.1.2 Protocol messages

We describe the specific messages that are used to establish the communication with the aircraft node when it performs a handover. In addition to the messages defined for the PMIPv6 in [CLP$^+$08] and the LISP [FFML13], we introduce a new MAPPING UPDATE message, that is used to update the mapping cache in the ingress Tunnel Routers (iTRs). The Table 2.4 summarizes all the terminology and message types used in the P-LISP.

3.1.3 Node entities

We firstly describe the role of each entity in the P-LISP and how to map them in the ATN/IPS network infrastructure.

the Aircraft

The aircraft hosts all the airborne critical end-system applications that need an IP communication with the ground systems. It can be seen as a simple mobile host or an mobile IP subnetwork. For now, the aeronautical stakeholders have not yet decided whether the end system applications should be an entire IP system or just an application on top the airborne router's IP layer, as shown in the Figure 2.10. In this thesis, we consider the aircraft as a mobile host (solution B), like in the ATN/OSI infrastructure. Taking this approach will ease the deployment onboard the aircraft, as only the transport layer needs to be adapted to be connected to an IP stack. However, the main drawback of this solution is its lack of adaptability to the new mobile IP devices such as tablets.

Message Type	Context
RS	When it receives a RA packet from the router with a new IP prefix, it tries to establish an IP link with the router. The packet contains the IP link local address of the aircraft.
RA	Routers send RA packet to advertise their prefixes to the nodes. They can send periodic and solicited RA packets.
pBU	pBU is sent by the AC-R when it detects a new mobile node attachment. After the mobile node is identified, pBU is sent with the mobile node's ID to the AG-R to get a new home prefix for the mobile node.
pBA	pBA is sent as a reply to the pBU containing the home prefix information
LISP MAP Register	LISP MAP Register is sent to record a new EID-to-RLOC association in the Mapping system. It comes with the IP address of the source as RLOC.
LISP MAP Notify	LISP MAP Notify is sent in reply to the LISP MAP-Reg if the bit MapNotify was TRUE
LISP MAP Request	LISP MAP Request is sent to the Mapping system when a router needs to forward data and does not know the RLOC associated to the EID destination
LISP MAP Reply	LISP MAP Reply is the reply to the LISP MAP-Req. It contains the RLOC information of the EID present in the LISP MAP Request packet.
MAPPING UPDATE	MAPPING UPDATE is sent from the mapping system to the subscribed routers as soon as an EID-to-RLOC has been modified in a registered eTR.

Table 2.4: Terminology and messages used in P-LISP

The addressing plan for the aircraft is based on the ICAO IPS addressing space, specifying that a 56-bit address space is assigned to aircraft in the new ATN/IPS infrastructure, which will be composed of a 32 bit prefix and the 24- bit ICAO aircraft ID [HL16]. The ICAO aircraft ID is unique and distributed by the ICAO. It is notably used by the ATC to detect and identify an aircraft with the mode-S radar.

In this configuration, the airborne router (A-R) is responsible to forward the packets from and to the applications. There is no need for implementing a routing protocol onboard with P-LISP or a mobility protocol. The unique function it has to implement is the link selection to forward download traffic. Based on the information from the different airborne radios (AeroMACS, LDACS, SATCOM, VDLm2, and so on) about their availability and link quality (if exists), the A-R will select the best Air-Ground subnetwork for each different application depending on their QoS requirements. This function will be discussed in more details in the next chapter of this thesis.

the Mapping system (MRMS)

It is an entity implemented in the ATN/IPS ground network. It is composed of a Map Server (MS) and a Map Resolver (MR). The MRMS is connected to the eTRs from which it receives LISP map registration messages and stores the EID-to-RLOC mapping into its database. Furthermore, it must advertise any new EID-to-RLOC mappings to iTRs that have already asked a mapping for this EID, in order to give them an up-to-date mapping information. The MR responds to LISP Map Request messages sent by iTRs, whenever an EID-to-RLOC mapping needs to be performed. The LISP specifies 2 modes to forward EID-to-RLOC mapping, the direct and indirect mode, as described in [CVS18]). Here, we choose to use the direct mode, where the MR directly replies to the iTR requesting the mapping, as it includes less signalling traffic in the core network, compared to the indirect mode where the

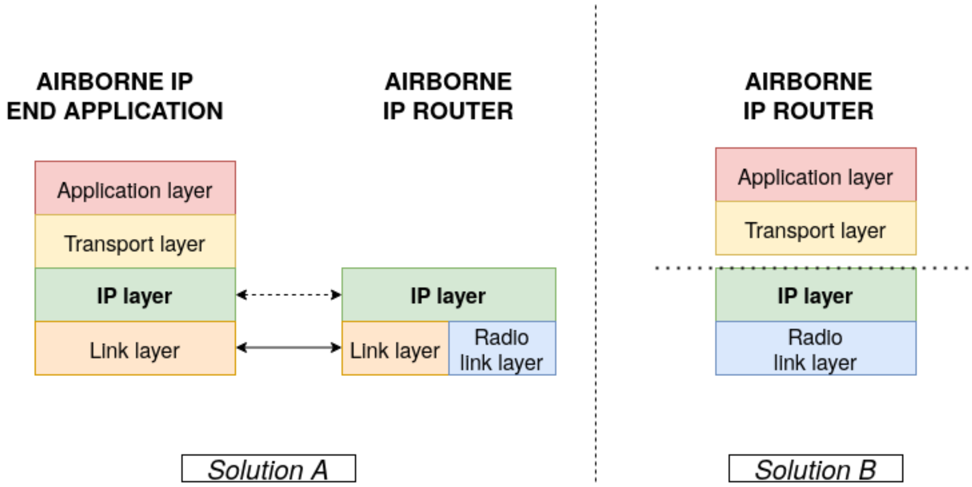


Figure 2.10: Model of aircraft to consider

MR conveys the request to the corresponding eTR which directly replies to the iTR making the request. Also, the question of the mapping update arises when mobile nodes need to be managed. The RFC [FFML13] proposes a solution based on a Solicited-Map-Request message (SMR). ETRs that update their mapping, when an aircraft joins or leaves their subnetwork, send a SMR message to iRTs to which they have sent encapsulated data for the last minute in order to tell them to make a mapping request to the MRMS to update their mapping cache. This solution needs 3 message exchanges to update the mapping cache in the iTR. At this time, it is still under experiment. In the P-LISP, we propose a publish/subscribe mechanism to update the iTRs' mapping cache. The MRMS, which has all the information, creates a group per aircraft's EID. When an iTR requests the mapping to an EID, it subscribes to the EID's group. Each time an eTR updates an EID-to-RLOC association, the MRMS sends a MAPPING UPDATE message to the EID's group with the new mapping information.

the Access Router (AC-R)

Similarly to the PMIPv6, the AC-R acts as a proxy router for the aircraft. It is the first hop router seen by the aircraft and responsible to authenticate and register the aircraft in the DSP domain. Whenever an aircraft detects a new network access and wants to establish a new connection, the AC-R will start the authentication procedure on behalf of the aircraft by querying the AAA server (outside of the scope in this work). After a correct authentication, the AC-R will register the aircraft in the A/G-R. The AAA server is out of the scope in our study.

the Air-Ground router (A/G-R)

In our proposal, this router must integrate the role of both the PMIPv6 LMA and the LISP tunnel router (xTR) through eTR/iTR mechanism, and thus allowing the aircraft to be connected to the rest of the ATN/IPS network. First, it will assign a home network prefix(HNP) to the aircraft based on ICAO IPS addressing space with 24 bits corresponding to the aircrafts ICAO ID. Then it will act as an eTR, meaning that it will use this HNP as the aircraft EID and register it with its RLOC address (i.e its routable IPv6 address belonging to the ATN/IPS domain) by sending a LISP MAP Register message to the Mapping System (MRMS).

In this way, ground end-systems willing to communicate with the aircraft HNP will send, through their G/G router, a LISP MAP Request to the MR in order to get the corresponding RLOC address. Reversely, when an aircraft initiates the communication to a ground end-system, its corresponding A/G-R acts as an iTR, meaning that it has to send a LISP Map Request to get the RLOC address attached to the ground end-system when it receives a packet from the aircraft. After receiving a non empty LISP MAP Reply, the A/G-R will store the mapping association in its local cache and then create a LISP tunnel to the G/G-R having the corresponding IPv6 RLOC address and send aircraft packets through this tunnel. In this way, for further incoming packets to forward, it just needs to use the corresponding tunnel. However, the authors in [HL16] highlights the first packet drop issue with the LISP. It means that while waiting for the non empty LISP Map Reply to arrive, the iTR deletes the packets because no EID-to-RLOC association is found for the EID destination address. As the aeronautical safety traffic is very low compared to common Internet traffic [RMS^{+}14], we allow the LISP router to store the first packets while waiting for the EID-to-RLOC association.

the Ground-Ground router (G/G-R)

It is a LISP router acting as an xTR to interconnect the Applicative Service Provider to the ATN/IPS core network. It is in charge of registering all the ground end-systems into the mapping system, and like the A/G-R, performing EID-to-RLOC mapping when packets need to be sent to the aircraft.

The Ground router (G-R)

The Ground router are located in the core ATN/IPS architecture and just run basic IPv6 external routing protocols. They use IPv6 RLOC addresses to forward the packets.

The Figure 2.11 shows the deployment of our solution into the ATN/IPS. In the two following subsections, the details of the P-LISP are explained for the registration phase and both intra and inter-domain handover scenarios.

3.2 Registration and location phase

The registration phase, presented in the Figure 2.12 occurs before each flight. The aircraft has to find a subnetwork to register to the ATN/IPS. The details on how the subnetwork identifies the aircraft with the AAA server (proof of identity, security via a shared key and so on) are technology dependent and out of the scope. We assume that the subnetwork know how to retrieve from the aircraft identity the aircraft EID. Once the L2 connection is established, the aircraft starts to receive RA packet coming from the access router AC-R$_1$, that triggers the NDP procedure (step 2 and 3). Then, the AC-R$_1$ triggers the binding procedure in the subnetwork to give a HNP to the aircraft (step 4, 5b and 6). Following this step, the A/G-R$_A$ must report the new aircraft location to the rest of the ATN/IPS. For that, it sends a LISP MAP Register packet to the MRMS with the aircraft EID together with its RLOC IP address (step 5a).

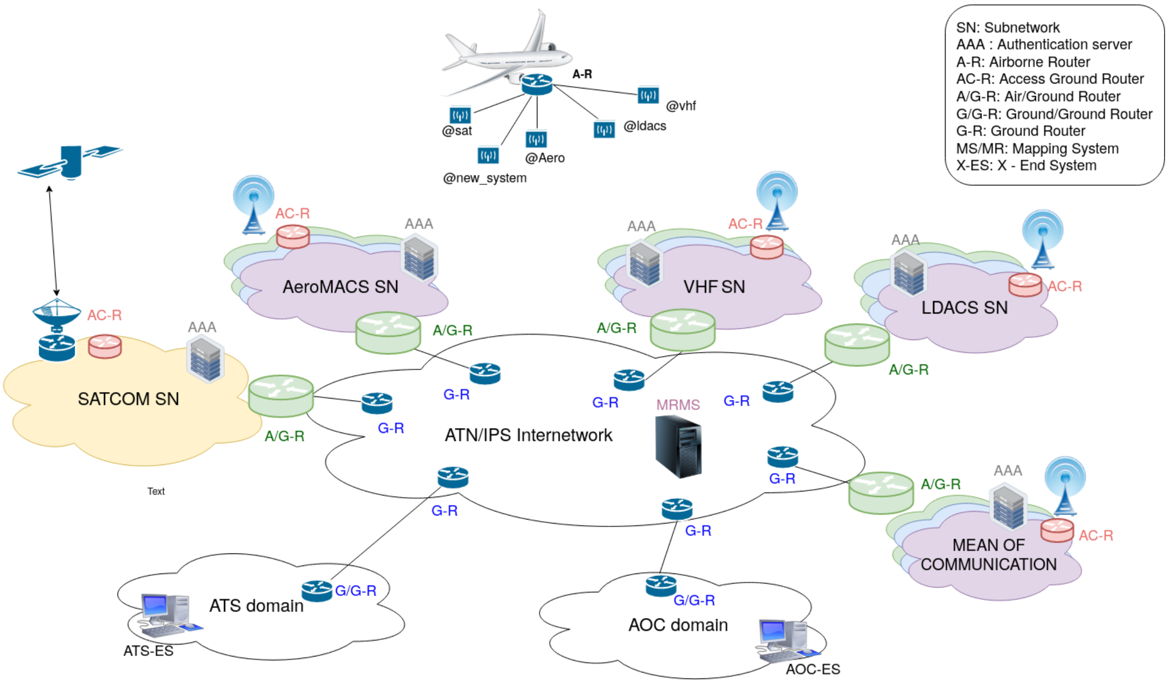


Figure 2.11: P-LISP deployment in the ATN/IPS

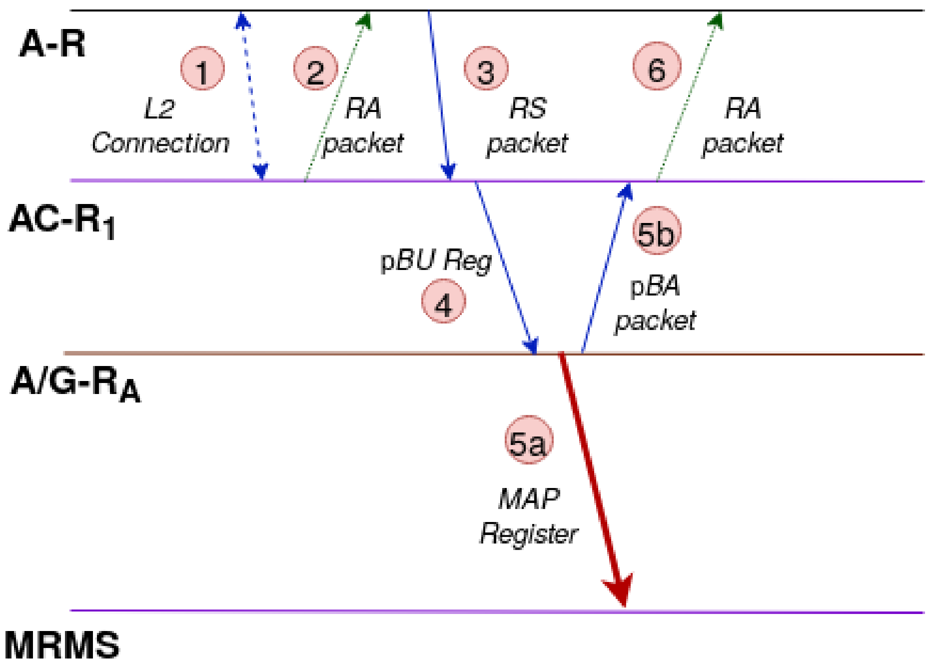


Figure 2.12: Registration and location phase

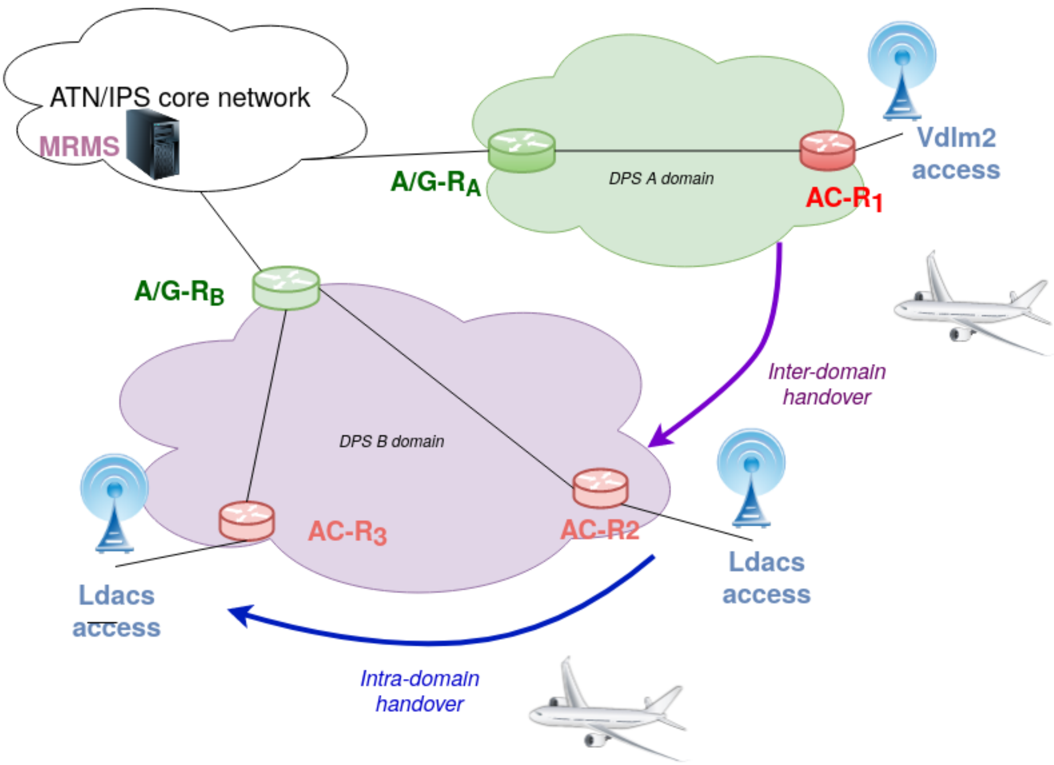


Figure 2.13: Intra and inter-domain handovers with P-LISP in the ATN/IPS

3.3 Inter-domain handover management

In inter-domain handover management, the aircraft handovers between 2 AC-Rs belonging to different DSPs' IP domain. Therefore, the aircraft location must be updated in the MRMS, as the aircraft is associated to a new RLOC address.

3.3.1 Case scenario

An inter-domain handover can be performed when an airline company subscribes to more than one DSP services. Indeed, in the context of the ATN/IPS, a lot of datalink services will be deployed in the future. One can choose to just offer a VDLm2 access network, while an other only proposes a LDACS access network. In this case, for an airline subscribing to both offers, their aircraft will perform inter-domain handovers, as described in Fig 2.13. The aircraft is firstly reachable via a VDLm2 access network provided by the DSP$_A$ (through A/G-R$_A$) and handovers to a LDACS access network provided by DSP$_B$ (through A/G-R$_B$).

3.3.2 Sequence diagram

The Figure 2.14 describes the different steps involved in an inter-domain handover. Firstly, the previous link must be disconnected. These steps are represented in red circles in the Figure 2.14. The step 1, 2 and 3a allow the subnetwork to acknowledge the link disconnection. The aircraft first perform a disconnection at the layer 2 which triggers the binding deregistration message exchange between the AC-R$_1$ and its A/G-R$_A$ (step 2 and 3a) to erase the entry corresponding to this aircraft is their tables. Besides, the A/G-R has to inform the rest of the ATN/IPS that the aircraft is no longer reachable in its subnetwork. This is performed by the step 3b after the timer set by the reception of the pBU deregister message timeouts. The A/G-R$_A$ is waiting for no incoming registration of this aircraft in its domain, and then sends a LISP MAP Register message to the MRMS with a lifetime equal to 0s to report the aircraft disconnection. Then the MRMS is spreading this information with a MAPPING UPDATE message to the multicast group of this aircraft EID (step 4). In parallel, the aircraft establishes a connection with a new link provided by the DSP B (step 5, 6, 7a, 7b, 8a, 8b). After detecting a new link by receiving a RA with a new prefix, the aircraft sends a RS packet to the AC-R$_2$, which starts the PMIP registration phase by sending a pBU register message to A/G-R$_B$ (the authentication step is omitted here). The A/G-R identifies the aircraft EID and looks for the aircraft HNP information. We do not detail in this work how the HNP information is retrieved, but C.Kim and al. in [KHBL13] propose to associate all the LMA (so here the A/G-R routers) in a multicast group to share the information of the HNP prefix. After getting this information, the AG-R$_B$ sends a pBA packet toward the AC-R$_2$ (step 7a) to report the successful binding, which in turns sends a RA packet with the HNP (step 8a). The aircraft, while receiving this information just updates the timer for this prefix has it already have an address with the HNP prefix. Meanwhile, the A/G-R$_B$ transmits the new EID-to-RLOC association to the MRMS via a LISP MAP Register packet. Then the information is transmitted to the G/G-Rs that subscribed to the aircraft's EID multicast group.

3.4 Intra-domain handover management (or local mobility)

In intra-domain handovers management, the aircraft handovers between 2 AC-Rs belonging to the same DSP's IP domain. Therefore, only mechanism related to the PMIPv6 is executed and no LISP MAP Register is sent to the MRMS.

3.4.1 Case scenario

An intra-handover case scenario can be performed when a DSP deploys many AC-Rs in its domains. For instance, it can choose to deploy one AC-R for each link technology, or several AC-Rs per link technology depending on the geographical position. The Figure 2.13 illustrates the second case scenario, where DSP B provides a LDACS access with two dedicated AC-Rs (AC-R$_2$ and AC-R$_3$). For the sake of clarity, all the ground stations subnetwork are represented by one ground station in the graph (for any kind of ground access network).

3.4.2 Sequence diagram

The Figure 2.15 illustrates the intra-domain handover in the case case scenario described above. Likewise, the procedure is split into two parts: the disconnection (red circles) and the new connection (blue circles). Steps 1, 2

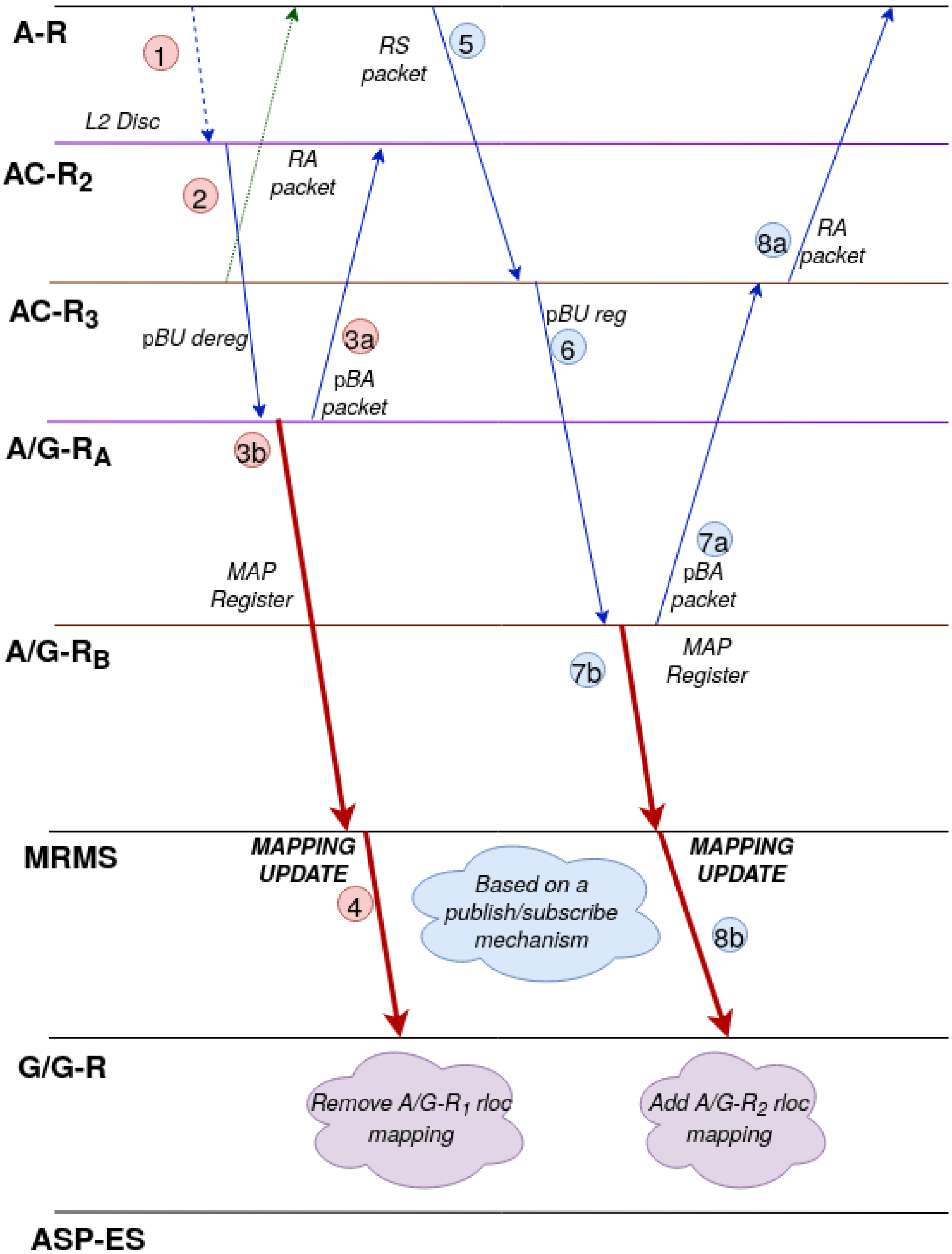


Figure 2.14: Inter-domain handover sequence diagram

and 3 are the disconnection of the aircraft to the router AC-R$_2$. At the step 2, the A/G-R$_B$ starts a timer and waits for a new binding from this aircraft. Steps from 4 to 7 is the traditional PMIPv6 binding procedure to attach to a new access router (AC-R$_3$ here) that happens before the timer timeouts, so that the A/G-R$_B$ does not have to inform the MRMS of the change.

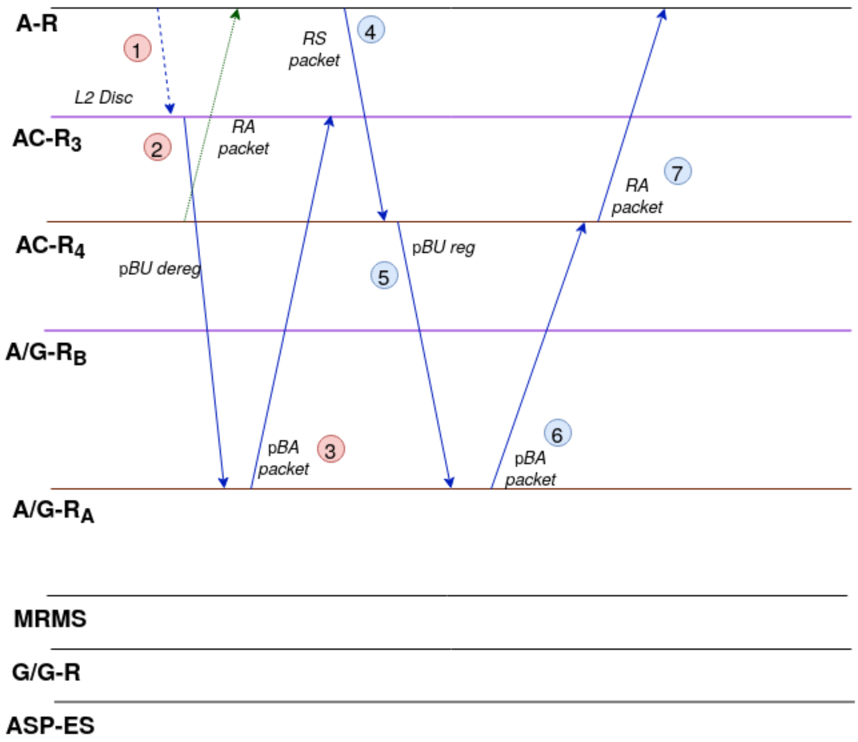


Figure 2.15: Intra-domain handover sequence diagram

4 Performance assessments

After describing the theoretical part of the P-LISP, we assess its performances in simulation by comparing with a standard mobility solution MIPv6+PMIPv6 that can resolve both intra and inter-domain handovers. We first describe the OMNeT++ simulated framework we developed for that purpose and then explain the results we obtain.

4.1 OMNeT++ network simulator

OMNeT++ is a a discrete event simulator [OMN] adapted for wireless communications. OMNeT++ is based on a modular architecture, thus make it simple to re-use existing modules and to develop our own ones. Among the frameworks developed in OMNeT++, INET [INE] is one of the most famous due to its high number of simulated protocols going from the PHY layer to the APPLICATION layer. In particular, the well known TCP/IP stack has been implemented with the IPv6 extension as well as the MIPv6, the standard IPv6 extension to handle mobility (referenced as xMIPv6 module in INET). A part of the INET framework will be reuse in the work such as the transport, application and physical layer and modules related to the IPv6.

4.2 Simulation framework

A lot of frameworks have been developed in OMNeT++ for different types of network such as VANET with SUMO (from 2016 to 2018) [SUM], WSN with CASTALIA (from 2007 to 2011) [CAS] or cellular networks with SimuLTE (from 2014 to 2019) [SIM]. Also, the INET framework has a IEEE 802.11 implementation that allows Wi-Fi communications with an access point. However, concerning aeronautical framework, none of them are suitable to simulate aeronautical subnetworks presented in the section 2.2, as each of them has their own authentication mechanism, that will impact the performances of the mobility protocols. In consequence, we developed a link technology module that will be more representative of the aeronautical environment. This will comprise layers from the physical to the link layer.

4.2.1 Wireless ground stations

Our simulation framework is based on the INET framework so that we can benefit from the IPv6 implementation. In this chapter, our goal is to study the network layer mechanism during a mobility scenario. Therefore, we do not implement a L2 node access point such as in the Wi-Fi model, as shown in the Figure 2.16 (left side). Instead, we choose to implement a wireless NIC (Network Interface Controller) inside the ATN/IPS ground router to simulate the L2 access point, as shown in the Figure 2.16 (right side). For our test scenario, the MAC protocol we use inside the Wireless interface is the CSMA (Carrier Sense Multiple Access), reused from the INET framework. But it is also possible to import other MAC protocols such as the TDMA used for LDACS technologies. The CSMA protocol is representative in the aeronautical subnetwork as the VDLm2 link technology is based on a similar protocol (CSMA p-persistent). To simulate the delay due to the connection between the router and the access point, we add up an extra delay before the router transmits a packet via the wireless NIC. For the physical medium, we reuse the *IdealRadioMedium* of the INET framework. It simulates an ideal propagation without taking into account radio interference. Parameters such as the bandwidth (31.5 kbps), the communication range (200km) and the propagation delay(from tens of ms to 1000ms) have been set up following the VDLm2 protocol. The benefit of this approach is that the ATN/IPS aircraft router is identical to ground routers, at least for the link and physical layer.

4.2.2 Handover model

Furthermore, as in the IEEE 802.11 that develops a handover mechanism between two Wi-Fi access points, a similar mechanism is necessary in our context at the link layer as it triggers the inter-domain handover at the network layer. In consequence, we develop a handover manager for the wireless NIC, illustrated in the Figure 2.17, that is able to switch between two different links based on a preference list. The choice of this policy is justified by the current

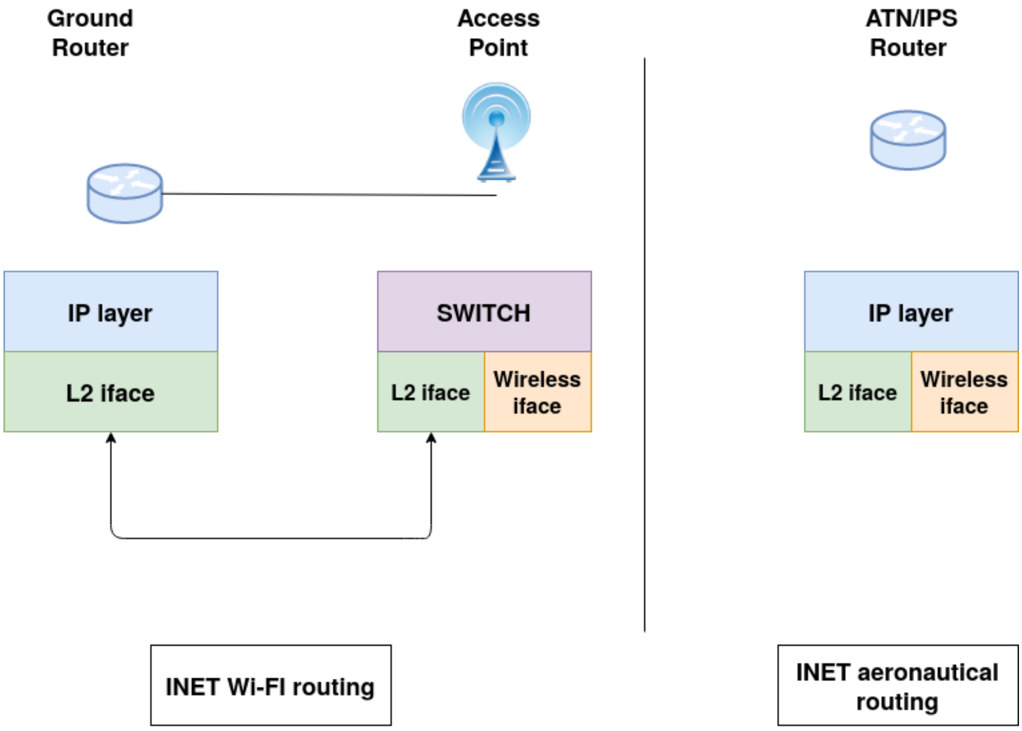
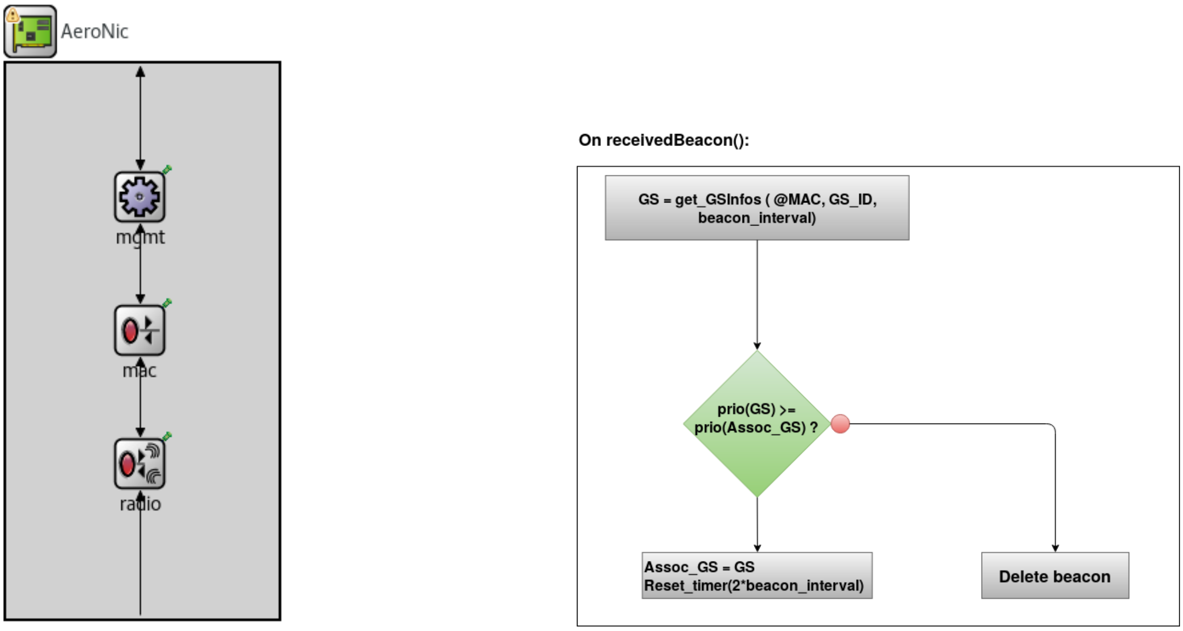


Figure 2.16: Ground Router representation

implementation of the handover model in airborne ACARS router. The handover manager module (mgmt in the Figure 2.17a) is connecting the MAC layer with the Network layer. The handover decision is made when the aircraft receives L2 beacon, following the algorithm in the Figure 2.17b. Each beacon contains the MAC address and the identifier of the sender, i.e the ground router. Beacons are periodically sent with a 300ms periodicity, similarly to the VDLm2 link technology deployed in the current aeronautical subnetworks with the GSIFs (Ground Station Information Frame) that are a kind of beacon gathering subnetwork information.

Validation test

To validate our link layer model with our handover manager, we test out a simple case scenario shown in the Figure 2.18 that uses the MIPv6 protocol at the IP layer to handle the aircraft network mobility. At this stage of the work, we just want to be sure that our link layer model with the handover manager works as expected, so the IP layer protocol chosen for managing the inter-domain handover is not important here. For the scenario, we consider one aircraft during its en-route phase at a cruise speed of 220 mps. It is first covered by IMS ground stations which belong to its Home Agent's (HA) subnetwork and flies towards a region only covered by SITA ones (foreign subnetwork). The overlapping area, corresponding to the area where the aircraft has an access to both IMS and SITA subnetworks, is about 50 km long. We consider that this aircraft has set up the SITA_EU subnetwork with the highest priority in this region. Besides, the aircraft sends ping packets at a time interval of 1s to the CN (Correspondent Node) on the ground. This value is arbitrary set to 1s and does not correspond to a specific aeronautical application.



(a) The aeronautical wireless NIC

(b) The handover management algorithm

Figure 2.17: Implementation of a handover manager

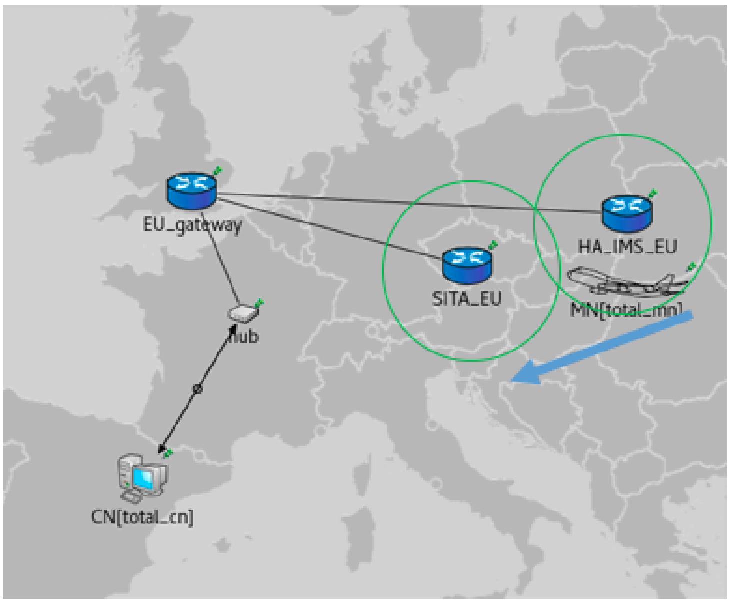


Figure 2.18: Test scenario for the handover manager

We conducted several simulations with two different setups: one with the handover manager (called HM scenario) and one with only the link layer described in the subsection 4.2.1 (called LO scenario).

For the LO scenario, as only the *IdealRadioMedium* module is reused from the INET framework to simulate the wireless medium, there is no link mechanism to associate the aircraft with only one access router on a dedicated channel. Therefore, when the aircraft goes through the overlapping area, it will receive both network prefixes of IMS and SITA. The MIPv6 module running on the aircraft will thus try to attach to both access networks successively as it will continue to receive RA packets even after performing a binding with its new CoA. This phenomenon is known as the ping pong effect. A handover manager is therefore necessary to avoid this effect.

The Figure 2.19 shows packets received by the aircraft at the link layer. By inspecting the packet size (y-axis), we deduce their type, thus helping us to determine the impact of our handover manager system on the MIPv6. The simulation runtime is 700s, which is enough for the aircraft to flight over both covered regions. The aircraft starts to send ping packets at the time t = 200s. The first red vertical line (t = 227s) indicates the moment where the aircraft enters the overlapping area and the second red line (t = 430s) indicates the moment where the aircraft exits this area. Before the handover occurs, the aircraft only sees its HA, thus all the PING reply packets (with packet size 100 bytes (B)) come from the HA. The two graphs in the Figure 2.19 illustrate the same behavior in both cases (for $t < 224s$), therefore our handover mechanism does not impact this phase. It only induced an additional signalling traffic coming from the L2 beacons (with packet size 30B).

When the aircraft enters the overlapping area, it will have the choice between the 2 access routers. In the LO scenario, (the left graph in the Figure 2.19), between 220s and 430s, the aircraft also receives some PING reply packets from the SITA ground router, highlighting the ping pong effect. Those packets are longer (140B) than those sending by the HA (100B) because of the additional IPv6 header corresponding to the tunneling mechanism. Whereas in the HM scenario with our handover manager (the right graph in the Figure 2.19), the aircraft only receives PING packets of size 140 bytes, coming from the SITA ground router. Indeed, as soon as the aircraft detects the SITA ground router, it creates the binding and maintains it because the SITA subnetwork is given a higher priority, thus removing the ping pong effect. In addition, another way to look at the ping pong effect is to observe the packets of size 52B (BA packet) and 72B (BU packet) in the LO scenario. Indeed, these packets illustrate that the aircraft updates in permanence its binding status with its HA, highlighting the ping pong effect.

After the aircraft exits the overlapping zone (for $t > 430s$), packets are forwarded only by the SITA_EU subnetwork as their size equals 140B, meaning that the packets are tunneled with an IPv6 header. So for the HO scenario, the aircraft remains attached to the SITA_EU subnetwork while for the LO scenario, the aircraft finally performs the inter-domain handover and switches towards the SITA_EU subnetwork.

More interesting is the number of packet loss at the application layer in both cases shown in the Figure 2.20. For the HM scenario (blue squares), although there are still some lost packets, the number of loss is significantly reduced when the aircraft is covered by the two access networks (between 220s and 430s). For the LO scenario

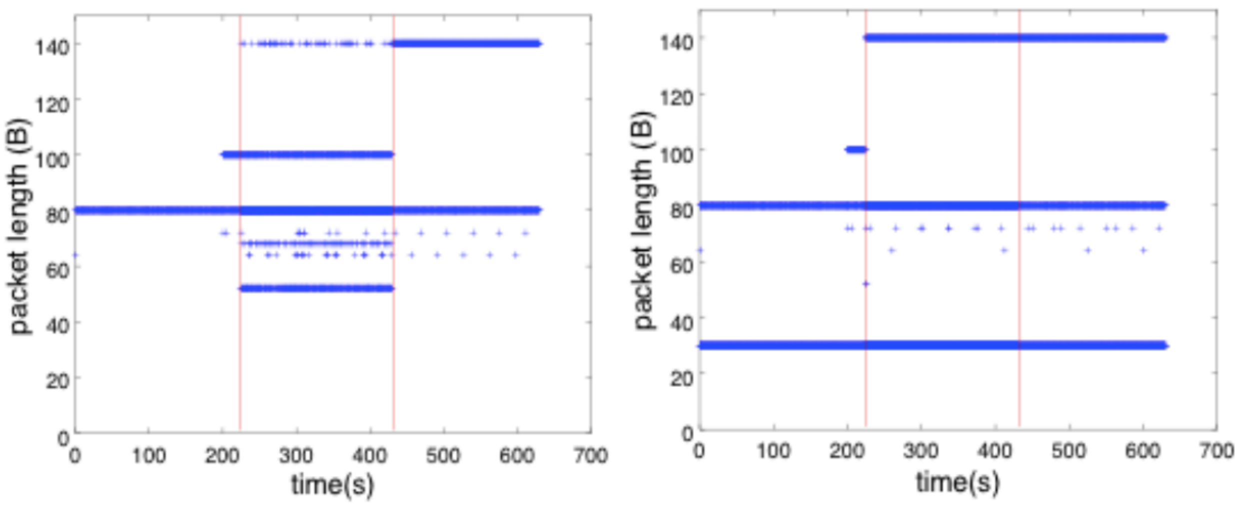


Figure 2.19: Packets received by the aircraft in LO (Link Only) scenario on the left, and in the HM (Handover Management) scenario on the right at the link layer

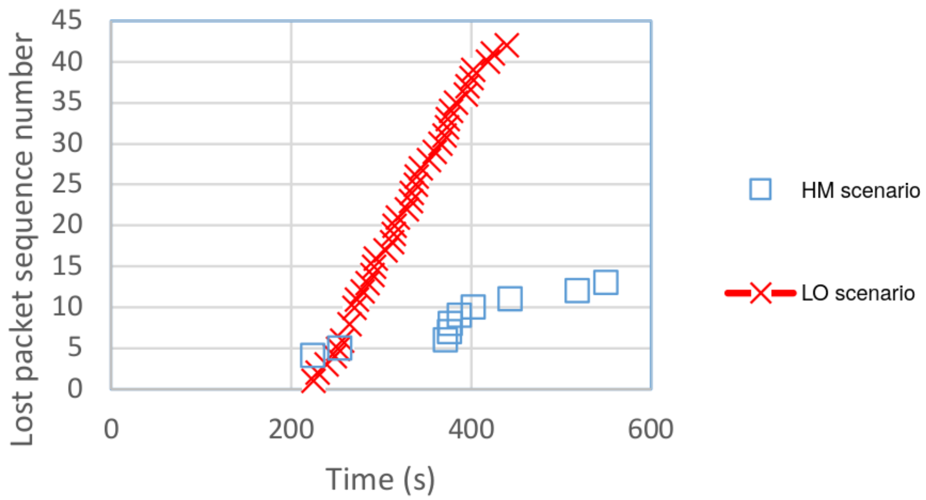
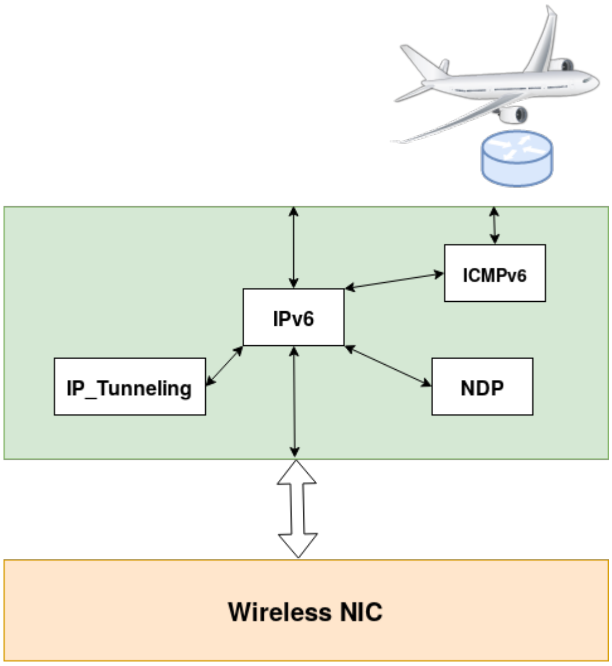


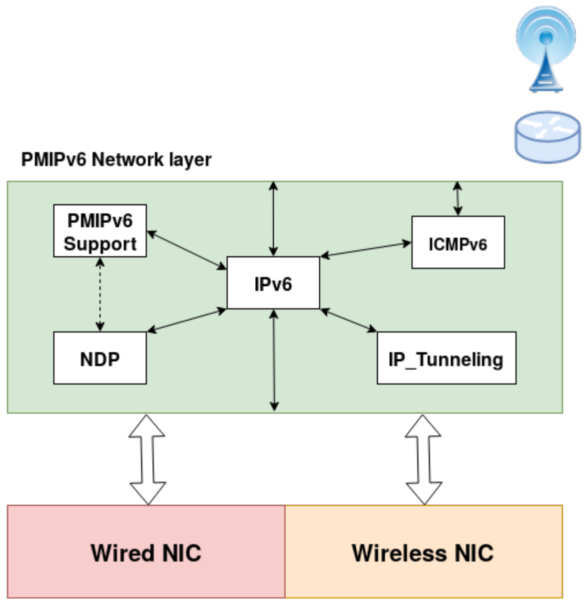
Figure 2.20: Packet loss for both case scenarios

(red cross), as pointed out before, the aircraft is keeping on changing its access router as soon as it receives a RA packet from the other access router. Thus, a lot of binding messages are exchanged(packet of size 70B in the left graph in the Figure 2.19), and during the exchange the link is not established so the aircraft cannot receive the PING reply.

These first results validate our handover mechanism proposal. It allows us to have a handover mechanism at the layer 2 enabling an IP mobility solution (MIPv6 here) to correctly perform the inter-dmain handover. This implementation has been presented in [TPL$^+$18].



(a) The aircraft router



(b) The Access router AC-R

Figure 2.21: Network stack of the aircraft and ground access router

4.2.3 Protocols implementation

Now that we have defined a proper link layer representative of an aeronautical environment with handover management at the link layer, we need to implement our IP mobility solution in the framework, namely P-LISP. In this subsection, we detail how the P-LISP is implemented in the different network entities in our framework. All the modules are based on the IPv6.

the Airborne router

In this chapter, we assume that the airborne router is equipped with only one wireless NIC under the network layer. The airborne router remains unchanged as only the IPv6 stack is required to perform the NDP procedure to change its address according to its point of attachment to the ATN/IPS. The network onboard the aircraft is presented in the Figure 2.21a. The IPv6 network layer is used and works as follows: the *IPv6 module* receives packets and based on their type, it forwards to the corresponding module (either ICMP packet, IP_Tunneling or ICMP packet for the NDP). Then, the corresponding module processes the packet and builds up the IP packet reply which is forwarded by the *IPv6 module* to either upper layers or the wireless NIC. For the DATA packets, if a route exists, the *IPv6 module* transmits the packet to the wireless NIC and for DATA packets coming from lower layers, the *iPv6 module* transmits it to the correct application above if the IPv6 destination address belongs to itself.

the Access router AC-R

The AC-R is responsible for the aircraft interconnection with the ATN/IPS. To do so, it must run the PMIPv6 to locate new mobile nodes and grant them a HNP. The implementation of the *PMIPv6* is presented in the Figure 2.21b (*PMIPv6 Support module*) and the module itself in the Figure 2.22. Inside the *PMIPv6 Support* module, the core code of the PMIPv6 is located in the PMIPv6 module, while the Bulist (Binding Update List) and the BCache (Binding Cache) represent data information stored in *the PMIPv6 Support module*. The PMIPv6 procedure is triggered inside the *NDP module* for AC-R nodes, by the reception of a RS message. Then, the *PMIPv6 module* looks into the BuList and checks whether a binding for the aircraft ID has already been set up. If not, the PMIPv6 procedure is triggered: a pBU (registration) message is sent from the *PMIPv6 module* to the *IPv6 module*. When the AC-R receives the pBA response with the HNP inside, the datagram is sent to the *PMIPv6 module* which writes the new binding in the BuList and triggers the *NDP module* to send the RA datagram containing the HNP to the airborne router.

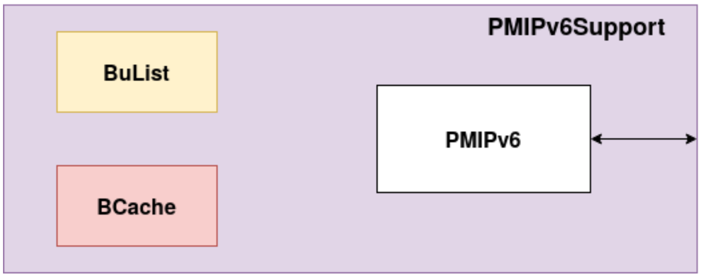


Figure 2.22: The PMIPv6 Support module

the Air/Ground router A/G-R

The A/G-R has the function of the LMA and the xTR. Therefore, it needs both the *PMIPv6Support module* and the *LISP routing module*. The global network layer architecture of the A/G-R is given in the Figure 2.23a and the *LISP Routing module* is depicted in the Figure 2.23b. The LISP code has been imported from the ANSAINET framework [ANS] and adapted to our P-LISP. The ANSAINET has been coded for IPv4 network, so we change all the addressing so that they correspond to IPv6 addresses. In addition, we modify the database information so that they support IPv6 addresses and establish the link between *the LISP Routing module* and the *PMIPv6 Network layer*. The main function of the LISP is located in *the LISP Core module*. The other 4 boxes represent database that are used in the LISP. *The MapDatabase* as well as *the MapCache* include information related to the EID-to-RLOC association between an aircraft and its locators (A/G-R). While *the Site Database* and *the ETR database* gather information related to the network initialization: they store the information of the different A/G-Rs that are LISP compatible in the ATN/IPS deployment.

When the A/G-R receives a new binding association from a AC-R, it will store the information in the BCache present in its PMIPv6Support module and then will trigger the *LISP routing module* to create the new EID-to-RLOC association. A binding cache entry includes the aircraft EID, the AC-R IPv6 global address linked to the aircraft, its HNP with the prefix length, and the expired timer corresponding to the binding. We use the publish/subscribe event mechanism of OMNeT++ to trigger this module. We create two new signals "NF_TRIGGER_NEW_EID" and

"NF_TRIGGER_DEL_EID". On the first signal, the *Lisp Core module* writes the new aircraft EID in the *MapDatabase module* and sends a LISP MAP Register packet to the MRMS with the association aircraft EID / self RLOC address. The packet is first transmitted to the *UDP LISP module* which encapsulates it in a UDP header, before going to the network layer. On the second signal, the *Lisp Core module* deletes the aircraft EID in the *MapDatabase module* and sends a LISP MAP Register to the MRMS with the lowest priority for this EID-to-RLOC association.

The other function the A/G-R has to fulfill is the data routing. When data packets are forwarded from the aircraft to the A/G-R, they are handled by the *LISP Routing module*, illustrated in the Figure 2.23b. The *LISP Core module* first checks in the *MapCache module* whether an EID-to-RLOC association exists for the packet's destination EID. For the first data packet, no information is available in the cache, so the *LISP Routing module* is sending a LISP MAP Request to the MRMS to get the RLOC address corresponding to the destination's EID. While waiting for the response, the data packets are inserted in a queue. When the LISP Map Reply is received with an EID-to-RLOC association, this one is stored in the *MapCache module* and packets in the queue corresponding to the EID are encapsulated in a UDP header and sent to the corresponding RLOC address.

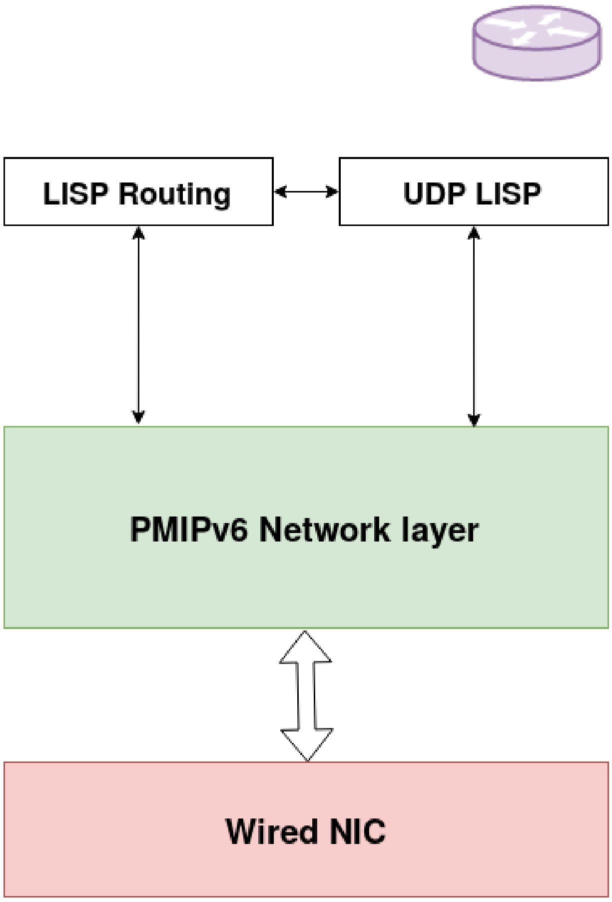
On the reverse direction, from the ground end-system to the aircraft, data packets arrive with a UDP header, so they are first forwarded to the *UDP LISP module* which decapsulates the UDP header and sends the packets to the network layer through the *LISP Routing module*.

the Ground/Ground router G/G-R

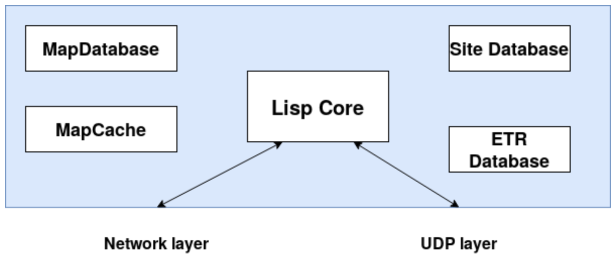
The G/G-R doesn't need the *PMIPv6Support module* as it does not handle mobile nodes. Therefore, it only implements a standard IPv6 network layer with the additional *LISP Routing* and *UDP LISP* modules. Such as the A/G-R, it is able to retrieve an aircraft's EID-to-RLOC association to forward a packet coming from a ground end-system. The network architecture of the G/G-R is presented in the Figure 2.24.

the Mapping system MRMS

The MRMS is the central entity in our mobility solution. It keeps track of the EID-to-RLOC associations and the xTR sites. Its internal structure is similar to the G/G router. During the initialization, all the ground routers acting as an iTR register themselves in the MRMS's *Site Database*. Whenever an eTR requests an EID-to-RLOC association, the MRMS creates an entry in the ETR Database at the reception of the LISP MAP Request. The ETR database lists the router's RLOC addresses requesting for a registered EID. It contains one entry per EID. Then it responds with a LISP MAP Reply to the eTR. When the MRMS receives a LISP MAP Register packet from a xTR site, it updates the information of this site in the *Site Database module* with the new EID information. Then the MRMS sends an UPDATE Mapping packet to the xTR sites that requested the EID-to-RLOC association for this EID. The information in the LISP MAP Register packet reports the state of the EID-to-RLOC association.



(a) The A/G-R router



(b) The LISP Routing module

Figure 2.23: Network stack of the Air/Ground router router

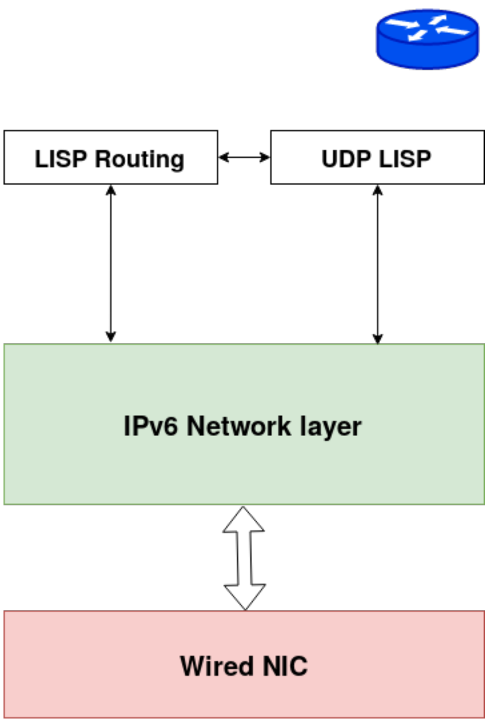


Figure 2.24: The G/G router

4.3 Simulation results

To assess the performances of our P-LISP solution, we compare it with a standard IPv6 mobility solution which is the combination of both the MIPv6 and PMIPv6, described in [GK16]. For that purpose, we adapt the xMIPv6 version of the INET framework to be compatible with our PMIPv6 implementation. The network infrastructure for the MIPv6/PMIPv6 solution is identical to our solution except that the Mapping system is replaced by the aircraft's Home Agent and the A/G-Rs only run PMIPv6. In this scenario, the Home Agent attributes a home address to the aircraft, which is based on the ICAO address. When the aircraft is connected to a DSP domain, it is given a home network prefix, so that it can build a IPv6 Care-of-Address (CoA) based on this prefix. After getting the new CoA, it informs its Home Agent of the new binding. We do not take into account the route optimization procedure of MIPv6 because the safety aeronautical traffic must always be forwarded to the Home Agent, which acts as a regulator entity. Both solutions are compared in terms of end-to-end delay, handover delay and traffic signalling. In addition, we compare the delay performances with the service requirements.

4.3.1 Case scenario

This study focuses on the performances of the different handovers at the network layer an aircraft has to perform during its flight. The scenario depicts an aircraft flying at a cruise speed of 250 mps, performing successively an inter-domain handover and an intra-domain handover as described in the Figure 2.13, except that we only simulate VDLm2 subnetworks. The link delays in the ground ATN/IPS network have been chosen to simulate a typical case of handovers happening only in Europe. Meanwhile, the aircraft receives downlink traffic from a ground end-system. We simulate a heavier traffic than the one proposed in [RMS+14] with an $IAT = exponential(10s)$. This value approximately corresponds to a traffic increased by a factor of 10, which is representative of the evolution of the amount aeronautical data traffic perceived since 2007, the date of the last COCR report. The application traffic uses the *UDP module* in the INET framework. The simulation lasts for 1200s, to allows the aircraft to perform both types of handovers.

4.3.2 Signalling analysis

In order to evaluate our proposal, we first compare the signalling involved by both protocols. The most stringent link in terms of resources is the wireless link, so we focus our analysis on the network signalling over this link.

Intra-domain handover

For the intra-domain handover, for both solutions, the signalling is induced by the PMIPv6 in which the aircraft first transmits a RS packet to the AC-R and then the AC-R replies with a RA packet containing the HNP. The total network traffic signalling over a wireless link for this phase is summed up in the Table 2.5.

Intra-domain handover	IPv6 header	Options	Total
RS packet	40	8+8	56
RA packet	40	16 + 8 + 2*12 + 24	112

Table 2.5: Intra-domain handover signalling (in Byte) over the wireless link

Inter-domain handover

For the inter-domain handover, our solution does not involve extra signalling apart from the RS/RA message exchange, as shown in the Figure 2.14. Whereas, with the MIPv6/PMIPv6 solution, after getting the new CoA, the aircraft is involved in a binding exchange with its Home Agent (Figure 2.27. The Table 2.6 summarizes the signalling traffic over a wireless link for an inter-domain handover. The P-LISP solution thus helps to save up to $72+52 = 124B$ per inter-domain handover. We do not take into account the fact that the binding with the Home Agent has a limited lifetime for security reason and needs to be renew after a certain period.

Mobility solution	Packet	IPv6 header	Mobility options	Total
P-LISP	RS	40	8+8	56
	RA	40	16 + 8 + 2*12 + 24	112
MIPv6/PMIPv6	RS	40	8+8	56
	RA	40	16 + 8 + 2*12 + 24	112
	BU	40	20 + 6 + 6	72
	BA	40	6 + 6	52

Table 2.6: Inter-domain handover signalling (in Byte) over a wireless link

4.3.3 Delay analysis

End-to-end delay

Another prominent factors of a mobility solution is the delay it induces on the application packets. The Figures 2.25 show the application end-to-end delay with both mobility protocols. There is not a big difference in the delay perceived at the application layer between both mobility solutions. The mean delay with the P-LISP is 0.195s and with the MIPv6/PMIPv6 solution, it goes up to 0.215s. Indeed, the only extra delay with the MIPv6/PMIPv6 solution is the RTT between the Home Agent and the Core network. In our simulation , the Home Agent has a link of 3ms with the core network. This value has been taken from [BA08]. This corresponds to a situation where the Home Agent is not so far from the location of the aircraft (in the same continent for instance Europe). But, the delay with the MIv6/PMIPv6 solution depends on the location of the Home Agent, which can increase in a situation where the Home Agent is at the opposite side of the globe.

Handover delay

Another delay to evaluate both proposals is the handover delay. Indeed, to allow a seamless service during the flight, the handover delay must be as low as possible to avoid packet loss. For the intra-domain handover, the delay is only due to the PMIPv6 which is common in both solutions. It corresponds to the delay from the moment when the aircraft drops its connection with its previous AC-R until the moment when the A/G-R updates its binding cache entry to insert the new aircraft's pCoA.

Concerning the inter-domain handover delay, we define it as the delay from the L2 disconnect signal emitted by the aircraft until the time it takes to the G/G-R to update its EID-to-RLOC mapping for the P-LISP scenario, and until the time it takes to the Home Agent to get the new aircraft's CoA for the MIPv6/PMIPv6 solution. This handover delay is based on three factors :

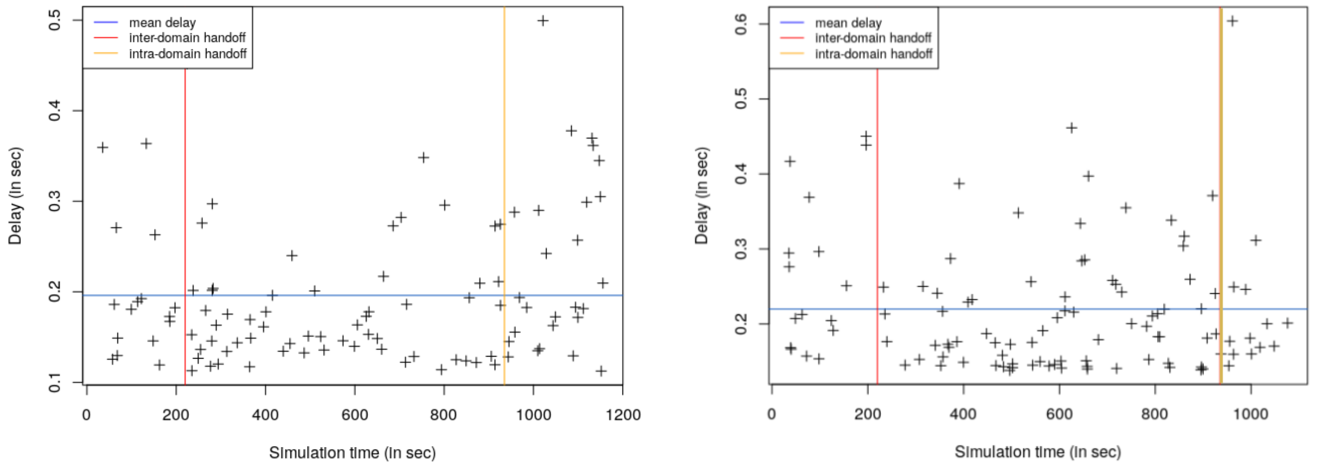
1. New link detection: it corresponds to the delay T1 until the aircraft get a new available link and transmits a RS message through this link. This time is mainly due to the air/ground datalink protocols and is not dependent on the network mobility solutions. In our simulation, we simulate a VDLm2 delay and we have a L2 switching mechanism that allows the on-board wireless NIC to be "connected" to a unique A/G datalink subnetwork.

2. Local update location: For the P-LISP, it corresponds to the delay T2 from the new link detection until the A/G-R gets the new location of the aircraft, i.e when it receives the Binding Registration from an AC-R. For MIPv6, it corresponds to the delay until the aircraft gets its new IPv6 address from the new home network prefix it receives. It includes the duplicate address detection the aircraft has to perform in order to validate the new IPv6 address.

3. Cache update: it is the delay T3 until the information of the new location of the aircraft reaches the router responsible to route the packet towards the aircraft. This router is the G/G-R for the P-LISP solution, whereas it corresponds to the Home Agent for the MIPv6/PMIPv6 solution.

Figures 2.26 and 2.27 show the complete inter-domain handover procedure for both cases. As said earlier, the handover delay depends on the link technology type. To provide more realistic results, we model the delay induced by the MAC sublayer before sending the packets. For instance, this delay is representative of a delay perceived by an aircraft attached to VDLm2 cell. This study is performed with the VDLm2 protocol developed under OMNeT++ at the ENAC laboratory. We show that the time in queue for downlink and uplink packets follow an exponential law with λ depending on the number of aircraft in the cell. The following results are obtained by varying the cell capacity from 20 to 200 aircraft (see Appendix A).

The delay T1 is identical for both case scenario as it does not depend on any network layer mechanism. We measure a delay ranging from 2.04s to 2.80s for our solution and from 1.8s to 2.53s for the MIPv6/PMIPv6 solution. The difference is due to the datalink protocol, which is in this case the VDLm2. For the time T2, we do not take



(a) Traffic application end-to-end delay with P-LISP **(b)** Traffic application end-to-end delay with MIPv6/PMIPv6

Figure 2.25: Comparison of the end-to-end delay with both mobility solutions

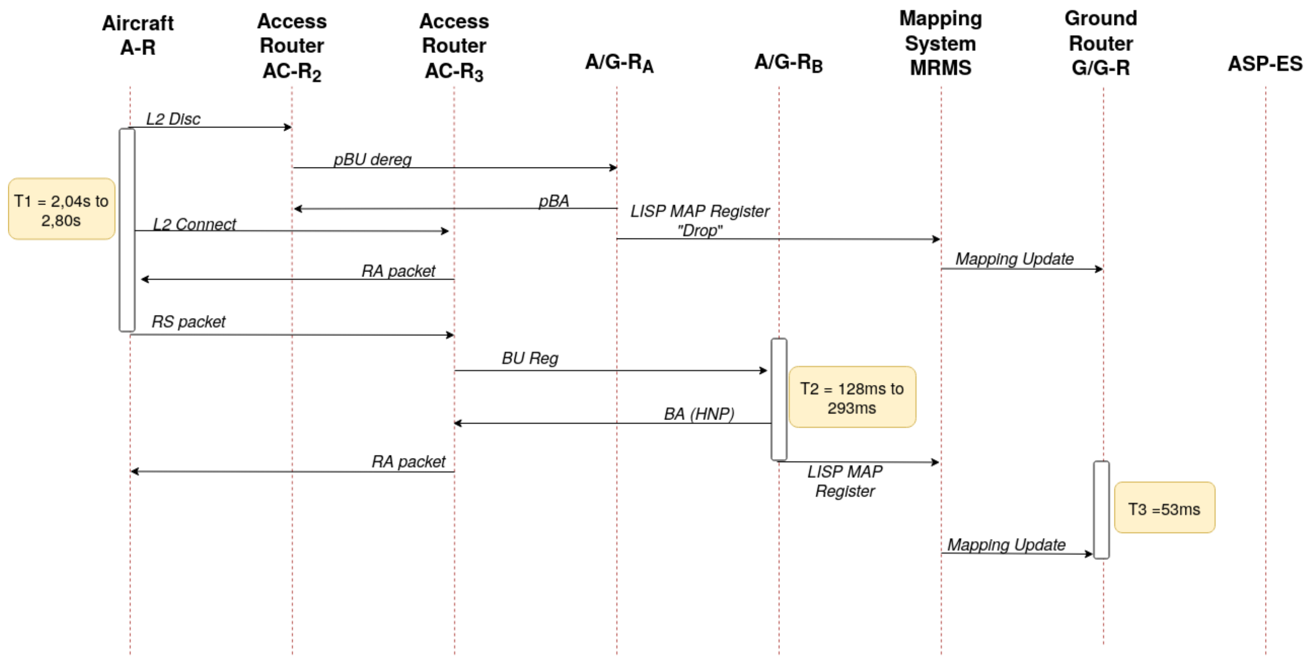


Figure 2.26: Inter-domain handover delay for P-LISP

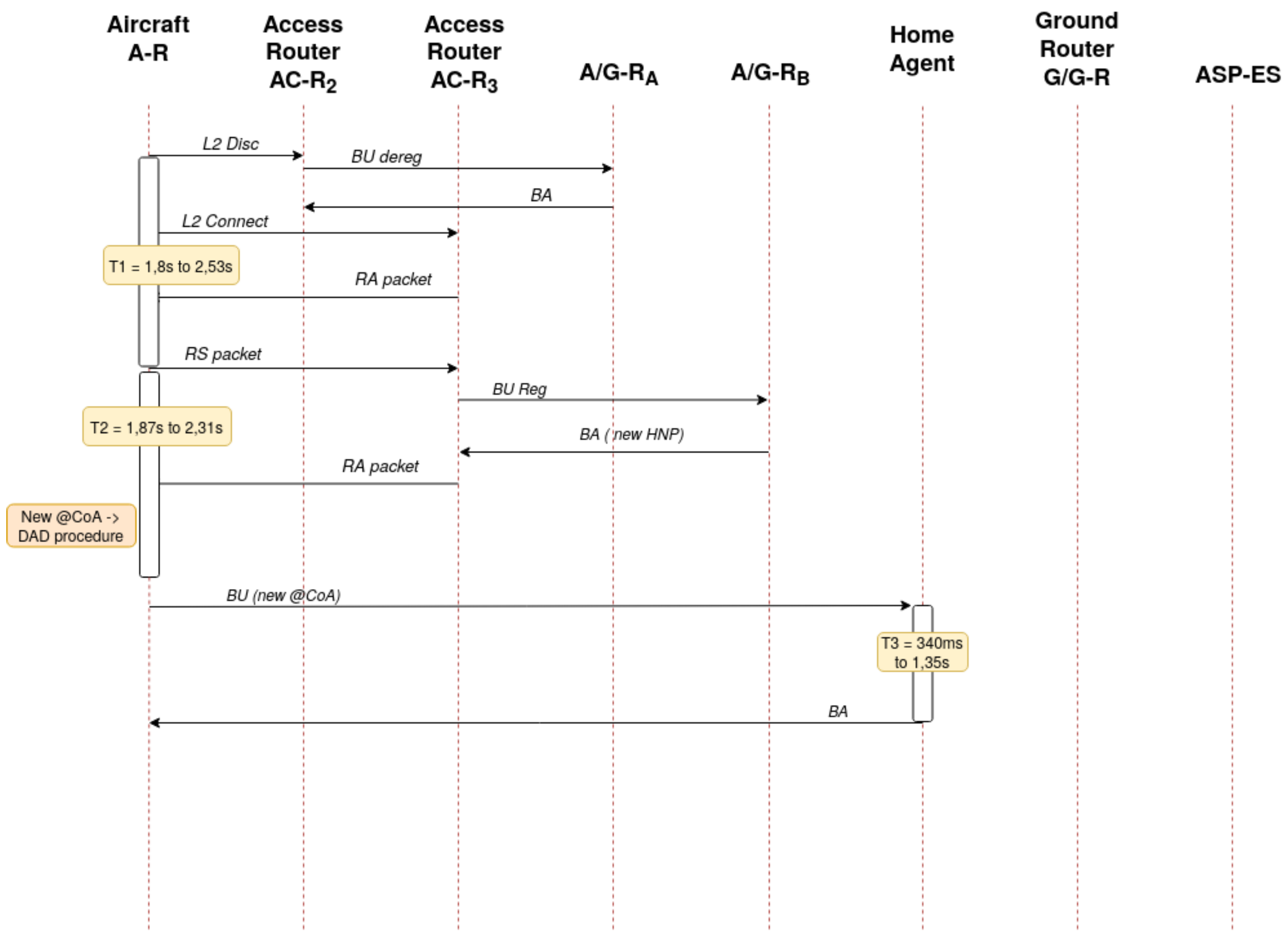


Figure 2.27: Inter-domain handover delay for MIPv6/PMIPv6

into account the time period until the aircraft receives the HNP inside the solicited RA message as it will receive the same HNP.The delay T2 is greater with the MIPv6/PMIPv6 solution because of the DAD procedure which takes approximately 2 seconds, 1 second to join the multicast group, and 1 second to be sure that no other nodes on the link is using the same address. For the P-LISP solution, the delay T2 only signalling exchange between ground routers, which is much faster. Indeed the T2 delay in this case goes from 128ms to 293ms. Concerning the delay T3, it is much shorter with our solution as the mobility signalling only concerns the MRMS and the G/G-Rs, unlike the MIPv6/PMIPv6 solution where the signalling involves the aircraft, therefore there is an important delay due to the radio link. Overall, with our solution, it takes 3,15s at maximum to perform the inter-domain handover whereas with the MIPv6/PMIPv6 solution, the inter-domain handover delay can reach 6,19s. This result proves that using a LISP-based solution can help to reduce the handover delay by a factor of 2.

4.3.4 Comparison with the requirements

In order to validate our model, we compare the simulation results with the QoS requirements of typical aeronautical applications. The most stringent requirements have been summed up in the table 2.2. From the perspective of the end-to-end delay, for handovers inside a same continental area such as Europe, the delay requirement is fulfilled for both the P-LISP and the MIPv6/PMIPv6 solution as shown in the Table 2.7. The computation of the mean expected delay is as follows:

$$mean\_exp\_delay = 2 * RTT * avg\_delay\_sol \quad (in \quad s) \tag{2.1}$$

Service	Delay (in s)	RTT	mean_exp_delay P-LISP (in s)	mean_exp_delay MIPv6/PMIPv6 (in s)
ACL	3.0	2	0.78	0.86
ACM	3.0	1	0.39	0.43
COTRAC	5.0	3.5	1.37	1.51
FLTPLAN	30	9	3.51	8.87

Table 2.7: End-to-end delay comparison with the service requirements

Given such low values for the average expected delay for both solutions, it is possible that these requirements can also be met if we consider that the aircraft and the CN are in a different continent. Indeed, the ground link delay between Europe and the United States are in the order of 0.2s [BA08], thus adding an overall delay of $4 * 0.2 = 0.8s$ for the ACL service, which gives in total an end-to-end delay of 1.58s for the P-LISP and 1.66s for the MIPv6/PMIPv6 solution.

However, regarding the handover delay, we have seen that the P-LISP solution needs 3.15s at maximum to perform an inter-domain handover, thus exceeding the requirement of the ACL and ACM services. For the MIPv6/PMIPv6, it is even worse with a handover delay reaching 6.19s, thus exceeding the COTRAC delay requirement. In conclusion, during an inter-domain handover, the performances are not granted for these types of applications in term of the end-to-end delay.

4.4 Simulation results summary

In this section, we provide a framework to evaluate 2 mobility protocols: our P-LISP solution and the standard MIPv6 enhanced with PMIPv6. We assess the performances of both solutions in terms of the traffic signalling generated over the radio link, the overall application packets end-to-end delay and the handover delay. For all of these criteria, our simulation shows that the P-LISP solution performs better, particularly for the inter-domain handover case scenario, as it does not imply the aircraft in its handover procedure. The comparison with the service requirements give a head to our P-LISP protocol compared to the PMIPv6/PMIPv6 solution as the P-LISP solution can meet the COTRAC delay requirement even during an inter-domain handover.

Conclusions

In this chapter, we first explained in which way the aircraft network mobility is different from other types of mobile nodes' network mobility. Indeed, the aircraft, due to its high mobility range, often needs to change its access point to the ATN/IPS. Depending on the geographical area and the coverage of each wireless link technologies, that may trigger either an intra-domain or an inter-domain handover. Then, a literature review has been conducted and all the IP mobility solutions have been compared. As none of them can respond to the aircraft's network mobility hurdle , we proposed a new network mobility solution to handle the aeronautical mobility case scenario. Our proposal P-LISP is based on the PMIPv6 to handle the intra-domain handover and the LISP to handle the inter-domain mobility handover. It is a full network-based mobility solution that has the advantage to keep the complexity on-board the aircraft as low as possible. To assess its performances, we developed a simulation framework in OMNeT++ based on the INET framework and compare our solution with a standard MIPv6 coupled with the PMIPv6. The MIPv6-based solution handles the inter-domain mobility with the help of a Home Agent that is responsible to track the aircraft location. Our comparison is based on three criteria: the traffic signalling over the wireless link which has the limited resources, the application end-to-end delay, and the handover delay. Overall, the P-LISP allows to have better performances. Indeed, the P-LISP allows to get rid off the signalling exchange with the aircraft to establish the new binding, thus reducing the signalling over the wireless link and also the handover delay, whereas with the MIPv6/PMIPv6 solution, there is a BU/BA message exchange with the Home Agent. That also explains why the P-LISP is two times faster than the MIPv6/PMIPv6 solution in terms of handover delay. In addition, the application end-to-end delay does not depend on a central entity (like the Home Agent), therefore its only depends on the ground routing protocol to efficiently route the packet in the ATN/IPS from two tunnel routers. On top of that, we have compared the end-to-end delay with the aeronautical requirements and the P-LISP has no trouble in fulfilling the delay requirement in nominal conditions. When an inter-domain handover occurs, it adds an extra delay that does not allow to meet the requirements anymore.

In conclusion, we have demonstrated in this chapter that the solution we proposed is a very good candidate to solve the aircraft's network mobility in the new ATN/IPS. In terms of the avionic architecture, this solution does not add any extra component on-board, compared to a MIPv6/PMIPv6 solution where the IPv6 stack need to be enhanced with the MIPv6 to handle Home Address and Care-of-Address.

Chapter 3

Multilink management: link quality evaluation

Contents

Introduction

The multilink concept in Telecommunications refers to the ability for a node evolving in a heterogeneous environment to use the different communication media at the same time or alternatively. In aeronautical communications, to provide a seamless connectivity to the aircraft and a more efficient end-to-end communication, several radio links are deployed, based on ground station antennas such as: the VDLm2's, the HF's and the future LDACS's and AeroMACS's ones, and satellites. Choosing the adequate link is crucial for ATM services as they need to meet highly demanding requirements in terms of performance delay, as shown in the Table 2.7, and packet loss as mentioned in the Table 1. To perform this task, the multilink algorithm requires 3 functions which are depicted in the Figure 3.1.

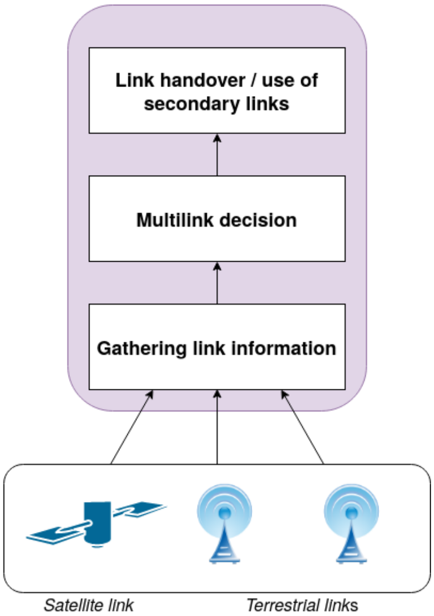


Figure 3.1: The generic multilink algorithm model

The chapter 2 gives the details on how to execute the third phase concerning the case of a handover. Our mobility protocol is able to establish a new connection to the aircraft as soon as a new radio link is available. It will result in either performing a handover to the new available link or using it as a secondary link for communication.

In this chapter, a novel approach will be detailed to provide link quality information to the decision algorithm onboard. The rest of the chapter is summarized as follows: Section 1 provides a state of the art on link quality metrics that have been used for the multilink decision algorithm in the context of wireless mobile communications in a heterogeneous environment, and explains why such techniques are inadequate to the aeronautical environment. Section 2 describes our proposed method to provide new link quality information to the onboard router. We will investigate both active and passive methods to measure the quality of the links. Our method is independent from the link layer, so it can be adapted to any current or future aeronautical link technologies. Section 3 shows the simulated framework in OMNeT++ we developed to validate our proposed method, and gives the results of our method. Section 4 concludes this chapter and gives some perspectives of further work related to this area.

1 Link quality information gathering

In current modern wireless communication network, the improvement of the network capacity and services is possible thanks to the integration of multiple wireless technologies.The use of multiple link technologies is twofold. First, it allows the network service provider to offer a global and continuous access to users which are able to operate on several link technologies. Secondly, it enhances the offered capacity via load balancing techniques when several link technologies are available. The multilink algorithm dedicated to perform this task, presented in the Figure 3.1, must first gather link quality information to decide at the next stage which link is the best to fulfill the QoS. In aeronautical telecommunication networks, we assume that the packet loss is guaranteed for all links otherwise, they must be disconnected. Besides, as critical aeronautical communication is very scarce compared to common Internet traffic, we assume that all the considered links offer enough capacity for transmitting the packets. Thereby, the QoS parameter that must be optimized for critical aeronautical applications is the delay (the Table 2.7 gives examples of the delay required for the most stringent critical applications).

1.1 Problem overview

Inside a homogeneous wireless access network environment, such as the 4G cellular network, a handover between two base stations is triggered by a single parameter: the signal strength is the usual metric to detect a loss of connection and to determine the best neighboring station to perform the new association. In the context of a heterogeneous environment, each wireless link has its own properties. They depend on the technology used at the link layer and the type of radio channel, so using only one metric such as the signal strength related to the physical layer is not sufficient. In order to compare these links, other links metrics may be considered such as the offered capacity, the mobile speed, the cell load and so on.

In aeronautical networks, the nature of each link as well as its properties is very different from one another. The Table 3.1 gives an overview of the typical values in aeronautical networks for the links that will be deployed in the ATN/IPS:

Technology	Throughput (Mbps)	One-way delay (ms)
VDLm2	31.5×10^{-3}	up to several seconds
Satellite	22	< 400
AeroMACS	14	$< 40 - 70$
LDACS	$0.1 - 0.3$	$120 - 552$

Table 3.1: Aeronautical link technology properties

In order to cope with this problem of link gathering information, we first review the state of the art on existing solutions that have been developed for other types of heterogeneous networks. Then, we will explain why these solutions have not been chosen in this work.

1.1.1 The IEEE 802.21 standard

The most relevant work related to retrieve lower layer protocols information has been carried out by IEEE 802.21 working group which proposes a modification in the network architecture to include the Media Independent Handover (MIH) layer [PP09][MTG14][dlOBS+08] between the network layer and the link layer, as shown in the Figure 3.2. It allows the network entities and the mobile node involved in the handover to communicate through an intermediate layer. This communication includes the exchange of information and commands related to the handover process. It is based on a set of predefined services named Service Access Points (SAPs). The IEEE 802.21 standard defines the communication between the MIH entitiy (MIHF) and the MIHF users, between the MIHF and the lower layers and between remote MIHF entities. Currently, these SAPS has been defined for certain specific technologies such as GSM (Global System for Mobile Communications), WLAN (Wireless Local Area Network), WPAN (Wireless Personnal Area Network), UMTS (Universal Mobile Telecommunications System), and WiMAX (Worldwide Interoperability for Microwave Access). These SAPs are classified into 3 different groups:

1. **Media Independent Event Service (MIES):** it was developed to support both mobile and network initiated handovers. Indeed, handover can be triggered at the MAC layer or the MIHF layer either located in the mobile node or a network entity. In order to perform a seamless handover, several node entities may be informed by this event to perform related handover function as soon as possible. To deliver this event, the MIH defines a subscription mechanism in which all entities willing to retrieve an event need to register to it. In this way, when this event occurs, it will be transmitted to all the entities in the subscription list. As said earlier, the IEEE 802.21 event service considers two types of events: MIH events and Link events. Link events are transmitted from the Link layer to the MIHF and the MIH events from the MIHF to the MIH users. Several event types may be delivered with MIH Event service:
   - MAC and PHY layer state change: an example of such an event is the Link Up event which informs of a connection to new available link.
   - Link parameters: when there is a change in the link parameter, such as the level of channel occupancy, it can be forwarded to upper layers. This report may be synchronous or asynchronous, meaning that it can be generated periodically or not.
   - Link Transmission: is emitted to inform of the status of higher layers PDUs transmission status. It may be useful during a handover as packet loss can occur.
2. **Media Independent Command Service (MICS):** defines a set of commands sent from the MIH users to the lower layers in order to retrieve some information about the link status or control a terminal to help the handover

execution. Firstly, this information, retrieved dynamically by the MICS, should assist the mobility/multilink management protocol to make its decision for a handover or using a secondary link. Secondly, network initiated handover is possible with the MICS, by sending a remote command by a network entity to a mobile node to force it to handover to a new base station. To sum up, there are two command categories:

- MIH commands: are sent by MIH users to the MIHF. In the case of a remote MIHF destination, the command is sent to the local MIHF which will transmit it to the corresponding MIHF via the MIHF transport protocol. Note that these commands do not directly impact the routing of the network layer which is left to a mobility management protocol.
- Link commands: are sent by the MIHF to the link layer upon receiving a command from the MIH user, in order to control the link layer or retrieve some information. This command can only be sent to the local link layers. However, it depends on the link layer technology. So any new link technology not yet specified in the IEEE 802.21 standard must implement these primitives to be able to interact with the MIHF.

3. **Media Independent Information Service (MIIS):** allows the MIHF inside a mobile node or network entity to retrieve network information to help the mobility/multilink management protocol to select the best access link. So all the different types of access network technologies must provide useful information to facilitate the mobile node handover. Such information is called Information Elements (IE) in the MIIS and are necessary to execute a seamless handover in this context. This information can be related to lower or upper layer protocols. As said earlier, the standard is only compatible with 802 and 3GPP networks. The IE is not linked with a link technology, so it is possible for a mobile node to get knowledge of network information with which it is not connected to via its current access network. For instance, a mobile node connected to a 4G network can get information about its surrounding WIFI access points. The information generated by MIIS is different than the one from the MICS in the sense that they are intended for being static information. This information is categorized into the following groups: general information, access network specific information, point of attachment, higher layers information and other information specific to different vendors.

1.1.2 Related work using the IEEE 802.21 MIH layer

Based on the MIH technology, many research has been conducted to improve the handover between cellular and 802 networks. De la Oliva and al. [MDLOS+06][dlOMV+07] [MCdlO+07] describe the implementation of the MIH to optimize the handover between WLAN and 3G networks. Besides, they use the MIPv6 to handle IP network mobility and shows how the MIH interacts with the MIPv6.

Other works study the handover between the WIFI and WiMAX network such as Figueiredo and al.[dFdSdSRdJP09], who study the impact of the handover in terms of packet loss and handover delay. Their study shows that the handover delay is linked with the RA inter arrival time in the IPv6. Based on the RFC 3775[PAJ04], this value should

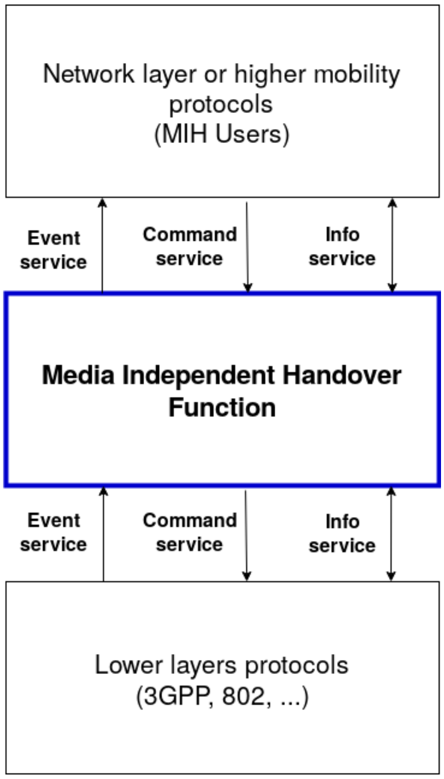


Figure 3.2: The Media Independent Handover layer

be between the interval MinRtrAdvInterval;MAxRtrAdvInterval = 0.03-0.07s. This value is set in ground IP routers and indicates the frequency with which they send a RA packet. For the minimum RA inter arrival time, the handover delay decreases. This is explained by the fact that the mobile node detects a new access network more rapidly by receiving a RA packet more frequently. Likewise, Tiwari and al. [TKG10] compare the performances of the MIH with different TCP versions, namely TCP Westwood+, TCP NewReno and TCP Vegas, based on the throughput, the handover delay and the packet loss. They conclude that the TCP Westwood+ performs better with the MIH in their mobility context scenario which implies a mobile node with a maximum speed of 20m/s. Chandavarkar and al. [CRRI11] propose a handover algorithm based on different parameters such as the battery life, the node speed, and the base station coverage. Jiadi and al. [FJL09] improve the link information gathering and link decision (step 1 and step 2 of the multilink algorithm) to reduce the handover delay and provide a better QoS. The study in [Rah15] realized by Rahil shows the limits of the MIH layer in the sense that it only provides a support for the vertical handover, by enabling the exchange of crucial information between the nodes responsible to execute the handover. Rahil proposes some improvements with respect to the MIH with a novel architecture that integrates the MIH and on top of that, a new decision module called VHMC managing different decision algorithms responsible to choose the new destination network for the vertical handover. Besides, it extends the MIH information exchanged by proposing a new data structure VHMC_LINK_DATA that gathers several physical and link information. Their results are based on a simulated NS-2 environment in which they evaluate the handover between WiMAX and WIFI networks. For instance, he showed that the handover delay is greater for a Wi-Fi to WiMAX handover compared to a WiMAX to Wi-Fi handover. Also, the handover delay decreases with the increase of throughput for all types of vertical handovers. This is due to the fact that with an increase in the throughput, packets are transmitted more rapidly, thus reducing the time interval between two packets and the handover delay in consequence. He also showed the limit of a simple decision algorithm which only considers the signal strength for the handover, compared to a MCSA (Multiple Criteria Selection Algorithm) decision algorithm that adds the available bandwidth to the decision parameter. These two decision algorithm have been assessed based on the packet loss ratio. The seconds performs better because it helps to reduce the number of handovers by always favoring the network with the better throughput.

Other work related to MIH have been focused on improving the mobility protocols thanks to the use of the MIH functions. These work have been conducted in a context of homogeneous networks. An and al. [YBK+06] define new MIH messages to help the MIPv6 by providing access points information usually retrieved by the IPv6 in the RS/RA messages.They show a decrease in the handover delay and the packet loss during a handover. Kim and al. [KJKK08] use the MIH to transmit the node geographical position in order to determine the best access point respecting its QoS requirements in the node surroundings. Another study, conducted by Ying and al. [WZYZ08], aims at improving the MIH functions by adding new events in the mobile node and network entities to trigger the handover at the link and the transport layer in the context of the VANET, represented here by a heterogeneous environment.

1.1.3 The Access Network Discovery and Selection Function (ANDSF)

The ANDSF is a function introduced in 3GPP TS 23.402 (Release 10) [3GP10], to help a mobile node using a 3GPP network to get access over non-3GPP networks such as WiMAX or Wi-Fi, that can be used for data transfer. The mobile node, called User Equipment (UE) in the 3GPP architecture, connects to the new ANDSF server which contains intersystem mobility and routing policies that can help the UE to discover and select available access network for handover (Figure 3.3). The ANDSF provides both push and pull methods for that regard, meaning that the UE can request the information or the ANDSF can initiate by itself the data transfer to the UE. To help the ANDSF make the decision of the most suitable access network for the UE, the latter may provide information to the ANDSF such as its location or its subscriber-specific networks. The three types of information provided by the ANDSF are :

- Access Network Discovery and Selection Information : is a list of access networks available in the UE's range with the type of the access network, network identifier, and so on.
- Inter-System Mobility Policies (ISMP): is a set of decision rules that applies the UE's data transfer such as whether 3GPP or non-3GPP access should be used, or the preference of a certain type of non-3GPP access or a preference of a non-3GPP access for the handover.
- Inter-System Routing Policies (ISRP): is a set of rules the UE must follows to route traffic over 3GPP or non-

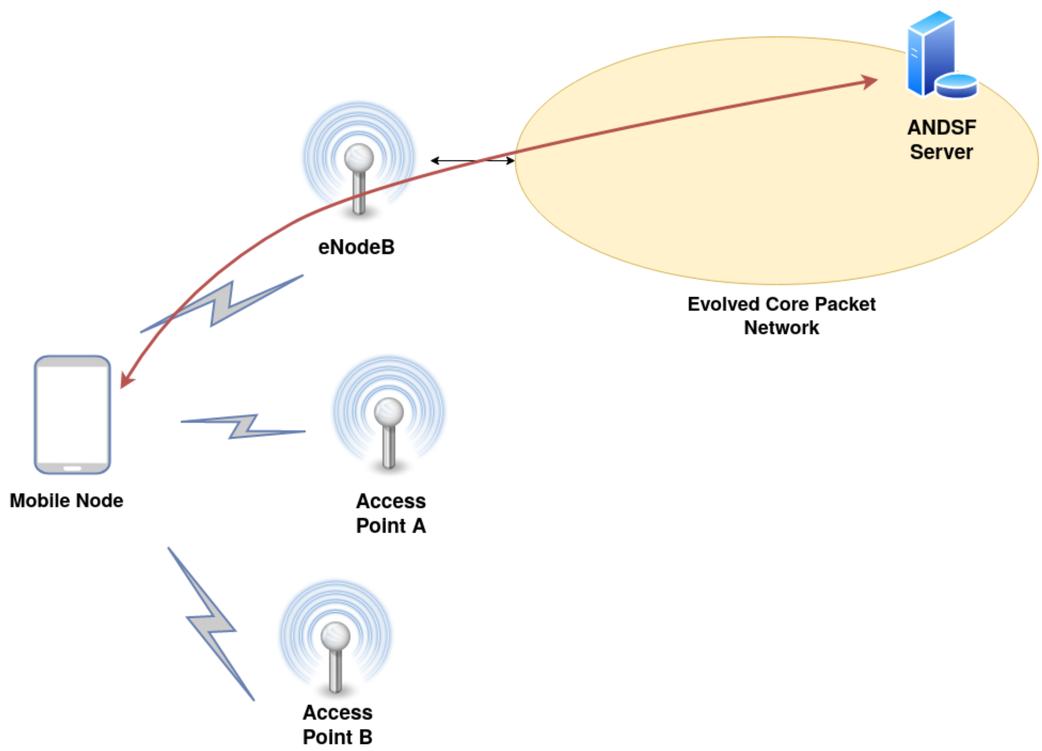


Figure 3.3: The ANDSF server in the 3GPP network

3GPP access networks. It includes routing policies for offloading the traffic to a WLAN for instance.

However, J.Orimolade and al. in [OVF16] highlights the limitations of the ANDSF, regarding the fact it does not take into account the current state of the available networks for offloading the traffic. To overcome this issue, they develop a Network Event Reporting function (NERF) at the access network level in order to obtain dynamic characteristics of the available access networks, which will feed a MADM algorithm to make the decision of the best available network for data offloading. Their results show that their method avoid offloading the traffic over congested network.

1.1.4 Aeronautical networks characteristics

Concerning the first phase of the multilink algorithm, in most of multilink algorithms published in the literature for standard mobile communications, link information that feeds the decision algorithm comes from the link layer, such as signal strength, signal-to-noise-ratio (SNR), available bandwidth, etc. It is assumed that such information is available for the mobile node via the MIH layer as seen previously. However, the aeronautical telecommunication network is very specific and is not taken into account in the development of both the IEEE 802.21 and the ANDSF standards.

Currently, they are three link technologies dedicated to safety aeronautical communications: SATCOM, HFDL, and VDLm2. The first two systems only provide a link status (link up/link down) as a link quality parameter, whereas the last one gives a signal quality parameter (SQP) and a channel utilization parameter (CU) mainly for performing horizontal handovers between VDLm2 cells. Due to these limitations, the multilink management on the onboard router applies static policy and is based on link failure (Link down event) before switching to another one. Concerning the load balancing, the router uses a unique link per type of application, meaning that packets emitted from two different applications can be routed via two different links, depending on the needed QoS.

Assuming that the future aeronautical link technologies will provide enough link quality parameters in order to help the multilink algorithm, implementing the IEEE 802.21 standard in order to homogenize the information requires first to add a new layer to the protocol architecture, which is very expensive for the avionics, and also to modify the existing link technologies so that they can provide enough information to be compared to the new ones. For these reasons, the approach of implementing a MIH like function has not been taken in this work.

The other approach described by the ANDSF standard is only relevant inside the Evolved Core Packet Network (EPC). As all the link technologies will be developed for the ATN/IPS, such handover mechanism described in the ANDSF won't occur as all the access network will already be compatible with the ATN/IPS intenretwork.

For the rest of the chapter, we will investigate link quality estimation techniques located at the network layer and above to not be constrained by the problems mentioned above. A similar approach to evaluate the quality of the link is used at the Transport layer that needs a congestion control mechanism to regulate the traffic flow based on the quality of the network links. For instance, the well known TCP congestion control mechanism infers that the RTT measurements directly reflect the state of the network, and thus the communication links. In the IoT (Internet of Things) domain, the CoCoA++ [RJS+19], and the RTT-CoAP [ABB18], two extensions of the Constrained Application Protocol (CoAP) [SHB14], also implement a RTT-based congestion control mechanism that dynamically adjusts the retransmission timeout (RTO) based on the RTT measurements. Like in the TCP, these IoT protocols infer that a packet loss, which is detected by the RTO, is due to a network congestion.

2 Proposed method to estimate the link quality in the ATN/IPS

In order to estimate the link quality, we will rely in this study on all the parameters in the network layer and above that are independent from the link technologies. This method aims at providing the more accurate link quality information to help the multilink decision algorithm to make the decision on when to offload the traffic and towards which link. This feature, combined with the multilink approach, will help the airborne IP router to fulfill the delay requirements of the critical applications 2.7, by removing the connection time to a new link when a traffic offload is necessary.

In the ATN/IPS, as mentioned in [HL16], we assume that the onboard router only needs to decide on the next hop router for packet transmission as the rest of the network links are fairly stable. The available routers send RA packets to inform the aircraft of a possible connection to the ATN/IPS. As of now, it has not been stated by the aviation authorities whether a DNS server or a Mapping system will be used to link the IP addresses with the ground end-systems. Therefore only the quality of the wireless link will be investigated here. In link metrology, the estimation is realized by either a passive or an active method.

2.1 Passive method

The passive method is a non intrusive method, as it is based on the traffic data to infer the link quality. In the ATN/IPS, we distinguish two categories of traffic: the data and the signalling traffic. The amount of data traffic related to safety traffic, is according to [RMS$^+$14] very low with a mean IAT from 110s to 225s representing a total of 15bps per aircraft for the downlink. The source of the signalling traffic comes from both the IPv6 network layer and the ATN transport layer.

2.1.1 Network signalling traffic

In the IPv6 protocol, the only regular signalling traffic is induced by the RA packets, which are periodically multicast by the access routers to the mobile nodes to announce their availability. However, the RA inter-arrival time specified in the RFC 3775, is a thousand times higher than the actual aeronautical application data traffic rate, inducing too much signalling, so we do not take into consideration the RA packets.

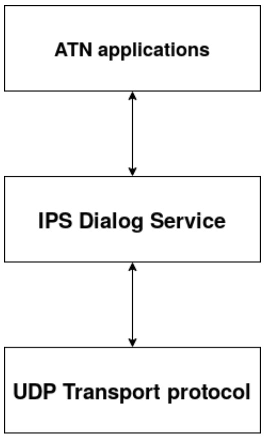


Figure 3.4: The ATN/IPS upper layer

2.1.2 Transport signalling traffic

It is expected that most of the safety aeronautical applications in the ATN/IPS will use the UDP transport protocol, which does not provide traffic integrity. This function is ensured by a Dialog Service (DS) entity, currently in use in the ATN/OSI network. It helps interfacing the ATN applications to the new IPS protocol stack (Figure 3.4), so that the ATN applications remain unchanged and easy to deploy. The DS-users starts the communication by exchanging a D-START/D-STARTCNF packet in which they set the binding parameters. The DS protocol uses the ATNPKT format, presented in the Figure 3.5 to convey its messages. The ATNPKT version shall be set to 1. The DS primitives are implemented over 4 bits as shown in the Table 3.2. The technology type shall be set to 0b000 (3 bits) for using the ATN/IPS technology. The More bit is reserved for using the segmentation and reassembly of UDP datagrams. The

Presence flags are a set of 12 fields indicating the parameters of the DS connection including source ID, destination ID, called peer ID, calling peer ID, QoS and so on. The complete details of these fields are provided in [Org09].

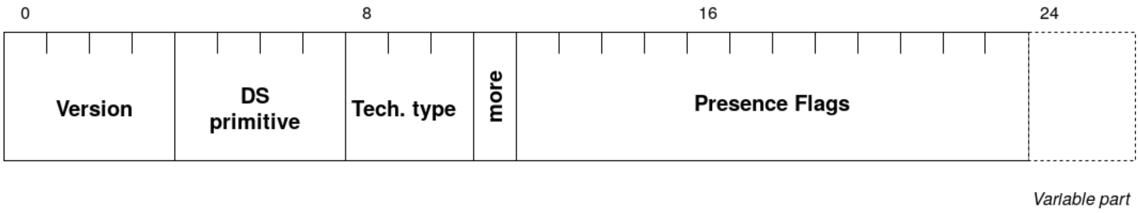


Figure 3.5: the ATNPKT format

For our purpose of measuring the link quality, one presence flag is particularly interesting, namely the Sequence number field. Its role is to provide a reliable mechanism to detect the loss and duplication of UDP datagrams as the UDP does not have any of theses functions. The Sequence Number fiels, illustrated in Fig 3.6 has the 8 bits format, 4 for each sequence number $N(S)$ and $N(R)$ (S: Sender and R:Receiver). The $N(S)$ is the sequence number of the ATNPKT sent and the $N(R)$ is the expected sequence number of the next ATNPKT to be received. The sender must wait for the DS-acknowledgement before sending the next packet. The Figure 3.7 illustrates a DS communication between a DS-sender and a DS-receiver. The communication starts with the DS primitives D-START and D-STARTCNF to establish the DS parameters. Then, each time the DS-Sender transmits a data packet, it increments its N(S) sequence number. When the DS-Receiver receives the packet, it copies the packet's N(S) value into its own N(R) sequence number and sends back the corresponding D-ACK packet with its N(R) value. The DS-Sender must wait for the D-ACK before transmitting the next D-DATA packet. When receiving a D-ACK packet, it checks the value of the N(R) field and if it corresponds to its N(S) value, it can transmit the next packet. If the DS-Sender doesn't receive a D-ACK with the matched N(R) value within a certain period, called *retransmission timeout* with a default value of 15s, it retransmits the D-DATA packet. Upon a certain number of retransmissions (between 1 and 10), the DS-Sender declares the connection as lost and sends a D-END primitive.

The number of retransmissions and the time to receive the D-ACK primitive is a good link quality indicator as it reflects the quality of the transmission. However, in the aeronautical context, as of now, the different available wireless links are divided into two categories: the primary and the secondary links. Primary links are used for the data transmission, while secondary links are used as backup. Passive techniques can be only used on primary links, and cannot help the multilink decision algorithm in choosing a secondary link where to offload the traffic, in case the primary link does not meet anymore the QoS requirements.

Besides, in the literature, the passive measurement technique is more often deployed in central network entities, where several flows of data can be gathered and thus gives a better overview of the link quality [LO13] [Kög13]. Thereby, the passive method has not been further investigated in our research as we are more focused on the aircraft side, which is an end-host in the ATN/IPS architecture. In the following, we will rely on active probing to

Value	DS Primitive
1	D-START
2	D-STARTCNF
3	D-END
4	D-ENDCNF
5	D-DATA
6	D-ABORT
7	D-UNIT-DATA
8	D-ACK
9	D-KEEPALIVE

Table 3.2: DS primitives

evaluate the quality of the wireless links.

Figure 3.6: The sequence number format

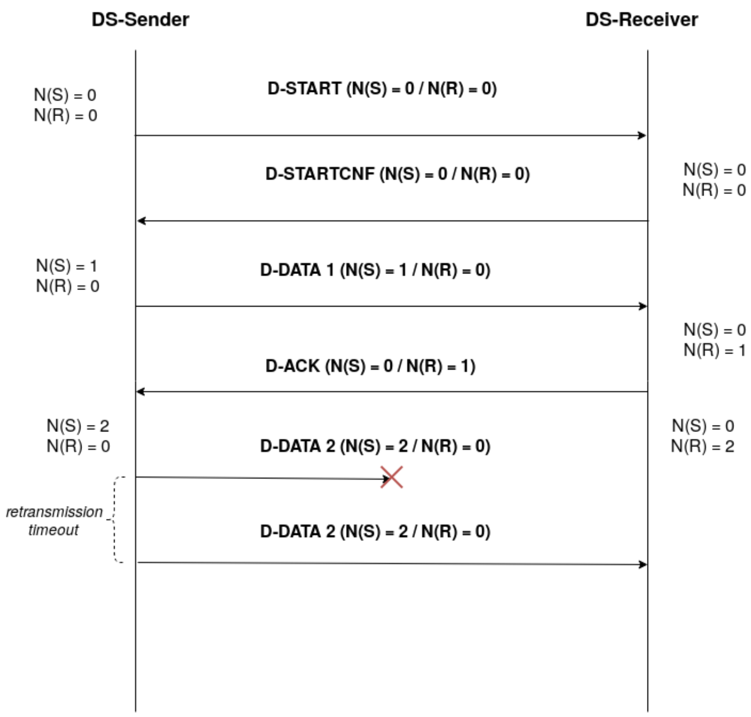


Figure 3.7: A DS sequence diagram with the sequence numbers

2.2 Active method

Active link quality estimation techniques rely on sending explicit packets, called probes, to retrieve link quality information. The advantage of this method is that probes can be routed toward secondary link in a heterogeneous environment, thus making the evaluation of these links possible. With the IP network layer, these probe packets are referred as ICMP (Internet Control Message Protocol) packets, with the header type field set to 08 for an echo request and 00 for an echo response, combined with the header code field set to 00. Upon receiving the echo response, the sender, which is in this case the ping application onboard the aircraft, gets the RTT between the destination node and itself. If the destination node is a ground end-system, the echo response might be routed through another wireless link depending on the ground routing policy. To avoid this situation, we set the TTL (Time-to-Live), or Hop Limit in the IPv6, at the IP network layer to a fixed value, so that the next hop router on the ground network sends back to the sender an ICMP packet corresponding to an expired TTL, with the header type field 11 and code 00. In this way, we ensure that the response packet follows the same wireless link as the request packet. The principle is illustrated in the Figure 3.8. The aircraft is using the SATCOM link for data traffic. After detecting a new wireless link (AeroMACS in this case), the aircraft's ping application starts sending probes that are routed to this link with the TTL field set to 1. Therefore, when the probe is reaching the AeroMACS access router, its TTL field is equal to 0, triggering the emission of an ICMP TTL EXCEEDED toward the aircraft via the AeroMACS link. The RTT measurement therefore represents the delay induced by the wireless link (AeroMACS in this example). It includes the propagation delay and the MAC queuing delay. In the context of the ATN/IPS, the propagation delay is very small compared to the MAC queuing delay and is thus neglected here. In consequence, the measured RTT is directly linked with the MAC queuing delay and so the channel congestion. However, in a wireless environment, the conditions may change drastically due to the MAC policy, bad weather condition or interference, so single values of RTT may not be sufficient to determine the channel state. In addition, as the aircraft may probe several links simultaneously, we must use the IP source address of the ICMP reply packet to determine which link service provider has sent the packet and therefore which link technology the aircraft is probing.

2.3 Estimating the channel capacity

In this part, we investigate different methods to estimate the quality of the different links based on the measures retrieved from the probe packets. Our goal is to predict the used capacity rate based on the measured RTT delays we get from the ICMP packets (detailed in the previous subsection). The estimation of this parameter will provide another relevant metric for the multilink decision algorithm. In this subsection, we will investigate three techniques to perform this task which are detailed in the following.

2.3.1 Threshold based

Due to the limited computing resource onboard the aircraft, we evaluate the feasibility of a basic classification method based on a RTT threshold detection. Given the value of only the instantaneous RTT, it is very unlikely that we are able to estimate the current state of the link. So we consider two features: feature 1($F1$) representing the current value of the RTT and feature 2($F2$) a history of the previous RTT values (can be a simple value such as

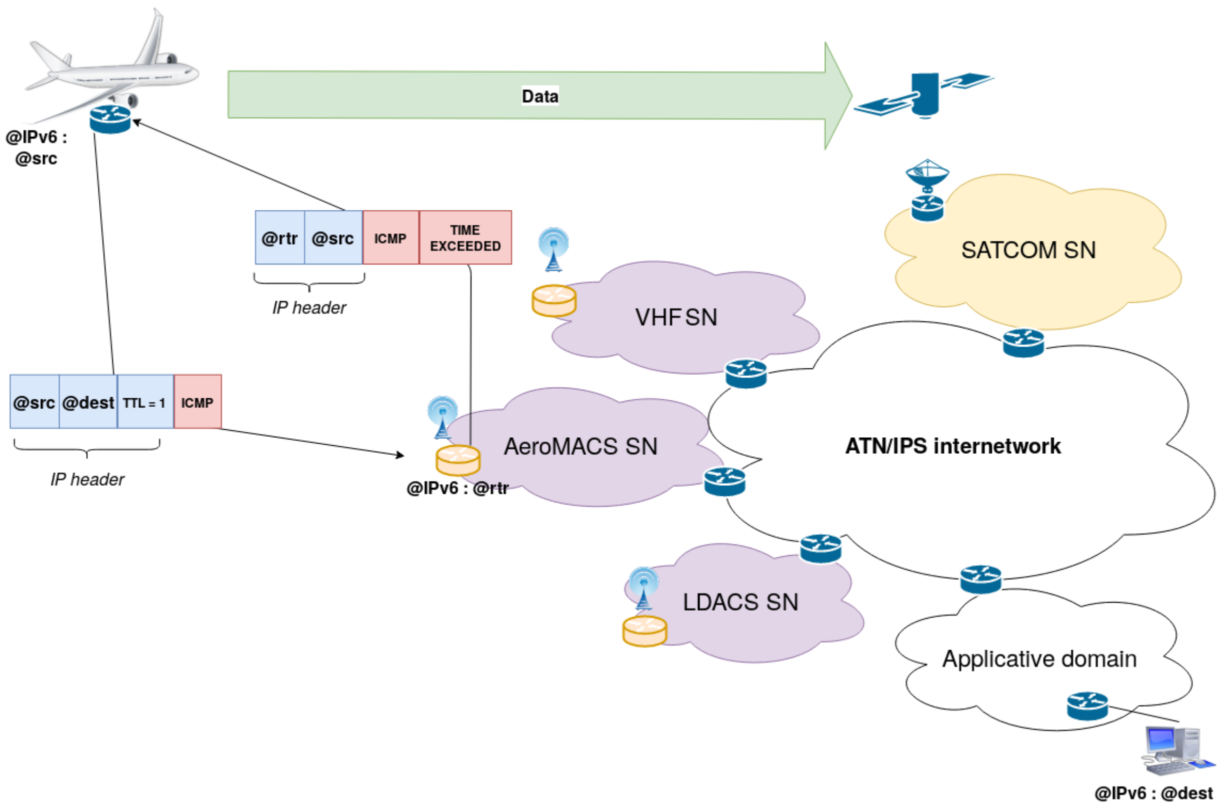


Figure 3.8: Probing in the ATN/IPS for link quality evaluation

the average of the history samples, or a list of values in the history samples). Then we represent the link quality by different states (from GOOD to BAD), representing different levels of used capacity rate. A GOOD state refers to a link with a low used capacity rate while a BAD state indicates a high used capacity rate. Let N be the number of states we consider (with N $>$ 2). For each of these states N_i, we define the threshold value (F_{min}, F_{max}), for each feature. Obviously, the value of the thresholds are link technology dependent, as the RTT delay differs form each link technology. The Figure 3.9 gives an example with N = 3, corresponding to a link state GOOD, MEDIUM, BAD. The size of the boxes depends on the values on the threshold values ((F_{min}, F_{max}) for each feature. In this example, the chosen features increase with the RTT delays, so a high value of the feature (1 and 2) indicates a degradation in the link quality. After establishing these different regions, we can thus deduce the link quality based on the RTT delays we obtain from the ICMP packets.

2.3.2 Markov model

We investigate another approach to deduce the quality of the link based on the RTT delays. This approach uses a Markov model which is a powerful statistical tool able to reckon pattern based on temporal data inputs such as the RTT delays history in our context.

Before the age of neural network algorithms in machine learning, one of the main techniques to estimate the

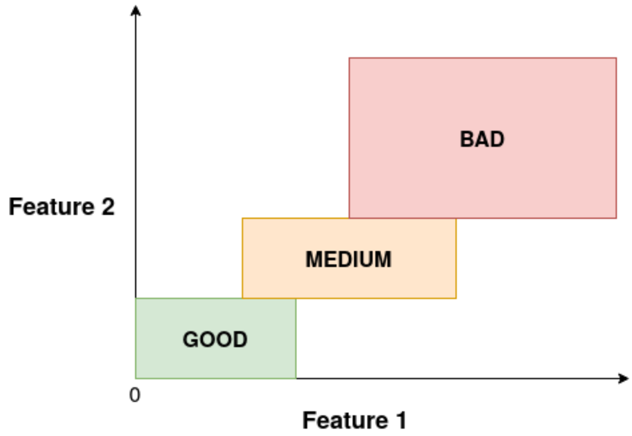


Figure 3.9: Threshold algorithm with N = 3

variation of a parameter was based on Markov models, and particularly Hidden Markov Models (HMM). HMM are often used in temporal pattern recognition such as speech [Rab89], handwriting, music [CN17] and also bioinformatics [ZSZ+04]. The network area has also shown an interest in the HMM learning algorithm. For instance, Chen and al. [CQ10], as well as Chang-hyun and al. [PKLS07] propose a HMM to predict the channel state of cognitive radio, and Akbar and al. [AT07] to predict the spectrum occupancy in order to dynamically allocate the spectrum resource in an efficient way. Another work in [SWYS10] conducted by Si an al. predict the user mobility in 4G cellular network by using a HMM. Also, Mitrakos and al. show in [MS16] that a HMM is able to recognize different types of traffic in wireless networks.

The HMM is a probabilistic method that can be used for predicting future events. Unlike the basic Markov model where the events are directly observable, HMM aims at predicting non observable state probability, called hidden states. To do so, HMM uses both observed events and hidden states. Let's call the hidden state at time t $S(t)$. The assumption behind the hidden state variables is that it follows a Markov process, so we can write $P(S(t+1) = r|S(t) = s) = p(r, s)$. This Markov process is characterized by the following components:

$\mathcal{Q} = q_1, q_2, ..., q_N$	the set of N states
$\mathcal{A} = (a_{i,j})$	the transition probability matrix $\mathcal{A}$ of dimension $N \times N$, where a_{ij} is the probability of being in the state j coming from the state i. Therefore, we have $\sum_{j=1}^{N} a_{ij} = 1 \; \forall i$.
$\pi = \pi_1, \pi_2, ...\pi_N$	the initial probability distribution over states. π_i represents the probability that the Markov process starts at state i. We thus have $\sum_{i=1}^{N} \pi_i = 1$.

To complete the HMM, we need to define the observed events, which are specified by:

$\mathcal{O} = o_1, o_2, ...o_M$	the set of M possible observations.
$X = x_1, x_2, ...x_T$	a sequence of T observations, taken from the set O
$\mathcal{B} = (b_{i,j})$	the emission probability matrix $\mathcal{B}$ of size $N \times M$, which only depends on the current state. This assumption is also known as the output independence. $b_{i,j}$ is the probability of observing o_j while being in the state q_i. We also have $\sum_{j=1}^{M} b_{i,j} = 1 \; \forall i$.

The Figure 3.10 illustrates how a HMM can be represented, where each plain arrow represents how the hidden state q_i and the observed event x_j are related, with the corresponding probability of such an event. In our case

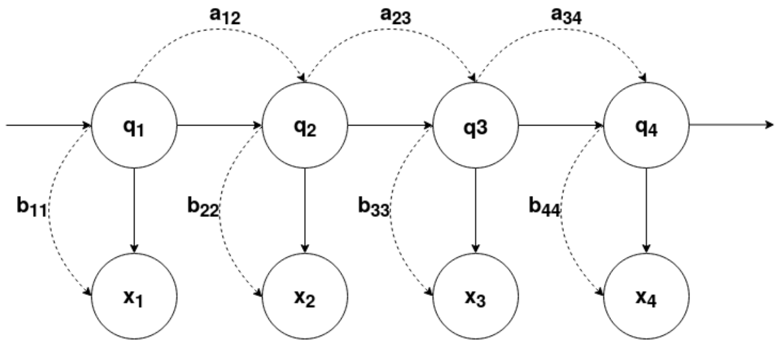


Figure 3.10: A HMM representation

scenario, the hidden state $\mathcal{Q}$ is the used capacity rate, which is unknown for the multilink algorithm, and the observed events $X = x_1, x_2, ...x_T$ are the RTT values which are obtained periodically with the active method described previously. One of the problems the HMMs are interested in is the prediction of the future states. This is also refers in the literature as **the Forward Algorithm**. From a sequence of T observed events $X = x_1, x_2, ...x_T$, **the Forward algorithm** gives the likelihood of this sequence of observations, noted L_T given by [CYZ13]:

$$L_T = P(X_{1:T}) = \pi \mathcal{P}_{X_1} \mathcal{A} \mathcal{P}_{X_2} ... \mathcal{A} \mathcal{P}_{X_T} \mathbb{1}^{\intercal} \tag{3.1}$$

where π is a $1 \times N$ vector, $\mathcal{A}$ is the state transition matrix of size $N \times N$ and $\mathcal{P}_{X_t}$ is a $N \times N$ matrix with P($X_t|s_i$) $(1 \leq N)$ on the diagonal and 0 otherwise. Then, using the Bayesian filtering approach, and the equation 3.1, we compute $P(Q_t = q_i|X_{1:t})$:

$$P(Q_t = q_i|X_{1:t}) = (\pi \mathcal{P}_{X_1} \mathcal{A} \mathcal{P}_{X_2} \mathcal{A} ... \mathcal{P}_{X_t - 1} \mathcal{Q}_i P(X_t|Q_t))/L_t \tag{3.2}$$

where $\mathcal{A}_i$ corresponds to the i^{th} column of the transition matrix $\mathcal{A}$. Given the previous equation 3.2, we are able to predict the distribution probability of the next hidden state by using the law of total probability:

$$P(Q_{t+1} = q_j|X_{1:t}) = \sum_{i=1}^{N} a_{q_i,q_j} P(Q_t = q_i|X_{1:t}) \forall j \tag{3.3}$$

where a_{q_i,q_j} is the transition probability from state q_i to q_j. The next hidden state Q_{t+1} is thus given by :

$$Q_{t+1} = \underset{q_i \in \mathcal{Q}}{\arg\max}\, P(Q_{t+1} = q_i|X_{1:t}) \tag{3.4}$$

A generalization of this pattern allows us to extrapolate the hidden state prediction up to time $t + T$, T $\in \mathbb{N}$. The algorithm is the following:

Algorithm 1 Prediction up to time t + T

Inputs:
sequence of observations $X_{1:t}$, transition matrix $\mathcal{A}$, emission matrix $\mathcal{B}$.
Initialize:
$F_t(q) = P(Q_t = q|X_{1:t})$
for k=1 to T **do**
State forward extrapolation Q_{t+k}:
$P(Q_{t+k} = q|X_{1:t+k-1}) = \sum_{i=1}^{N} a_{q_i,q_j} P(Q_t + k - 1 = q_i|X_{1:t+k-1}) = \sum_{i=1}^{N} a_{q_i,q_j} F_{t+k-1}(q_i)$, $\forall q \in \mathcal{Q}$
hidden state prediction $Q_T \leftarrow Q_{t+k}$ = $\arg\max_{q_i \in \mathcal{Q}} P(Q_{t+1} = q_i|X_{1:t+k-1})$
Prediction of next observation X_{t+k}:
$P(X_{t+k} = o|X_{1:t+k-1}) = \sum_{i=1}^{N} b(q_i, o) P(Q_{t+k} = q_j|X_{1:t})$, $\forall o \in \mathcal{O}$
Compute next state probability based on next observation:
$P(Q_{t+k} = q|X_{1:t+k}) = F_{t+k}(q) = \frac{b(q_i,o)P(Q_{t+k}=q|X_{1:t+k-1})}{P(X_{t+k}=o|X_{1:t+k-1})}$, $\forall q \in \mathcal{Q}$
end for

Therefore based on the Algorithm 1, we are able to compute the probability of all the link quality states $P(Q_{t+k}$ given a sequence of RTT measures $X = x_1, x_2, ...x_t$ up until the time t, for different values of k

2.3.3 Neural network algorithms

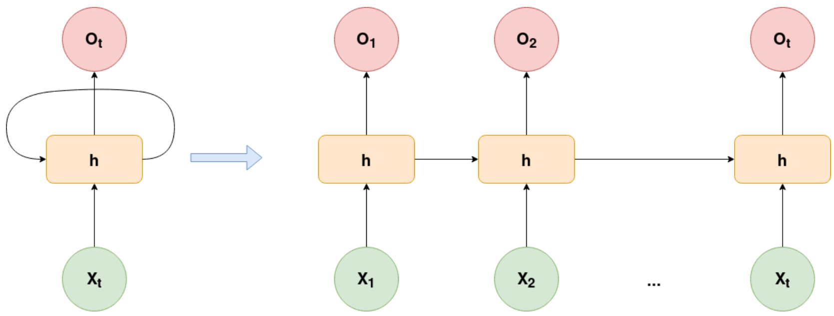


Figure 3.11: a RNN unfold

2.3.4 Neural network algorithms

Another popular kind of algorithms to perform the task of evaluation or prediction of a parameter given other features are machine learning based on neural networks algorithms. These algorithms are classified into two groups: supervised or unsupervised learning. In our context, we have a training samples where we can get both the inputs values (the RTT delays measures) and the output values (the used capacity rate of the link), therefore we will focus here in supervised learning techniques.

In the area of supervised learning algorithms, particularly in time series processing such as our case scenario where we deal with the history of the RTT delay measurements, recurrent neural networks (RNNs) have proven to be very efficient. For instance, Capizzi and al. [CSB$^+$17] use this technique for accomplishing a ”Smart VPN bonding” in order to efficiently establish the correct load balancing between two Internet mobile accesses. Indeed, RNNs takes not only the given input but also the output coming form the previous layer to be used as inputs as shown in the Figure 3.11. However, basic RNNs suffer from the vanishing gradient problem occurring when using a gradient based method to train the algorithm. As the gradient is back-propagated to the first layers, it becomes smaller and the weight cannot update its value. To overcome this problem, Long Short Term Memory (LSTM) neural networks are introduced by Hochreiter and Schmidhuber [HS97]. They allow to capture long term dependencies by introducing a cell state where previous information is either added or removed. Recent research in network have extensively used LSTM neural networks. For instance, Madhubabu and Thakre [MT19] predict the characteristics of a fast varying wireless fading channel in a moving receiver by using a LSTM neural network. Also, Chen and al. in [CXYX19] show that a LSTM network combined with genetic algorithm gives the best results in predicting the network traffic compared to traditional time series algorithms. An LSTM cell is composed of many gates as shown in the Figure 3.12. (The rectangular layers depict a neural network layer, while the red entities denotes mathematical operations.)

1. **the forget gate layer** f_t: its role is to only keep the useful information to process in the cell state. It is performed by a sigmoid layer which outputs a number between 0 and 1. 0 means the information is thrown away while 1 means it is still important.The equation of the forget gate is the following:

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \tag{3.5}$$

2. **the input gate layer** i_t **and the tanh layer** V_t: Both of these layers will decide what information to add in the new cell state. The update equations are the following:

$$\begin{aligned} i_t &= \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \\ V_t &= \tanh W_c \cdot [h_{t-1}, x_t] + b_v \end{aligned} \tag{3.6}$$

   From equation 3.5 and 3.6, the new cell state C_t is computed combining the new information and dropping the previous unnecessary information.

$$C_t = f_t * C_{t-1} + V_t \tag{3.7}$$

3. **the output gate layer** h_t: the output h_t is composed of the output gate o_t, which decides which part from the input and the previous cell output are relevant, and the cell state through a tanh operation.

$$\begin{aligned} o_t &= \sigma(W_o[h_{t-1}, x_t] + b_o) \\ h_t &= o_t * \tanh C_t \end{aligned} \tag{3.8}$$

(W_i and b_i are the learning parameters of the different neural network layers.)

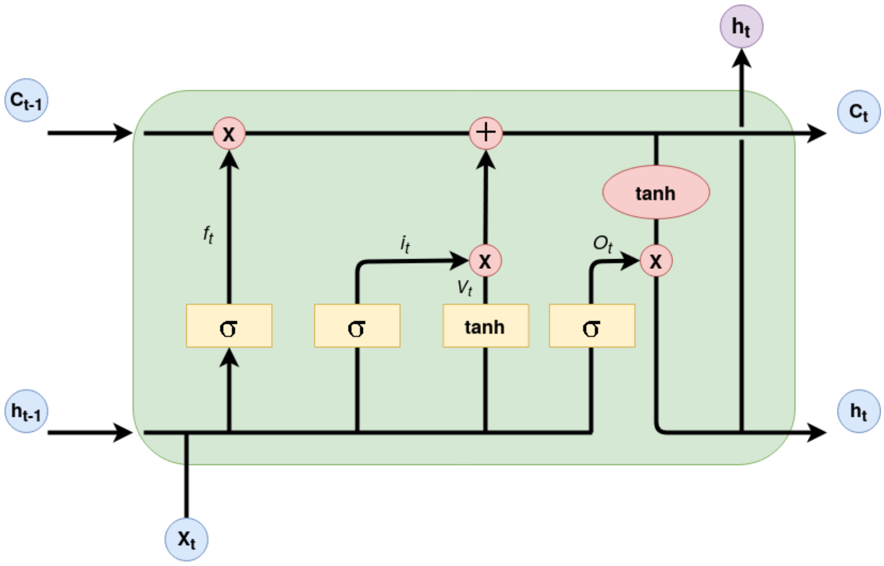


Figure 3.12: the LSTM cell

The goal of our deep learning network is to take a RTT sequence $X_{<T_x>}$ of length T_x given by the probe replies from the same link technology and to predict a sequence of future used capacity rate $h_{<T_y>}$ of length T_y.

3 Simulated framework

The previous section has presented an active method based on ICMP packet to obtain the RTT delays from the aircraft perspective. Then, three different techniques, based on threshold detection, Markov model and neural network, have been introduced in order to evaluate the quality of the different links regarding their used capacity rate. In order to demonstrate the benefits of our proposal, we use a simulated framework in OMNeT ++, called SAPIENT [VSLBR17]. This framework has been developed by the University of Pisa in the context of the H2020 Sesar project. In this section, we describe the SAPIENT framework and how our proposal is implemented inside this architecture.

3.1 SAPIENT framework

The SAPIENT project aimed at proposing an aeronautical simulated network in the context of the ATN/IPS. The SAPIENT framework implements all the network entities involved in the ATN/IPS (see Chapter 1). In the following, we explain how each entity is modelled.

3.1.1 The ATN/IPS modelization

The ATN/IPS is divided into three parts:

- the mobile subnetwork: is composed of aircraft that attach to the ATN/IPS core network via the access network.

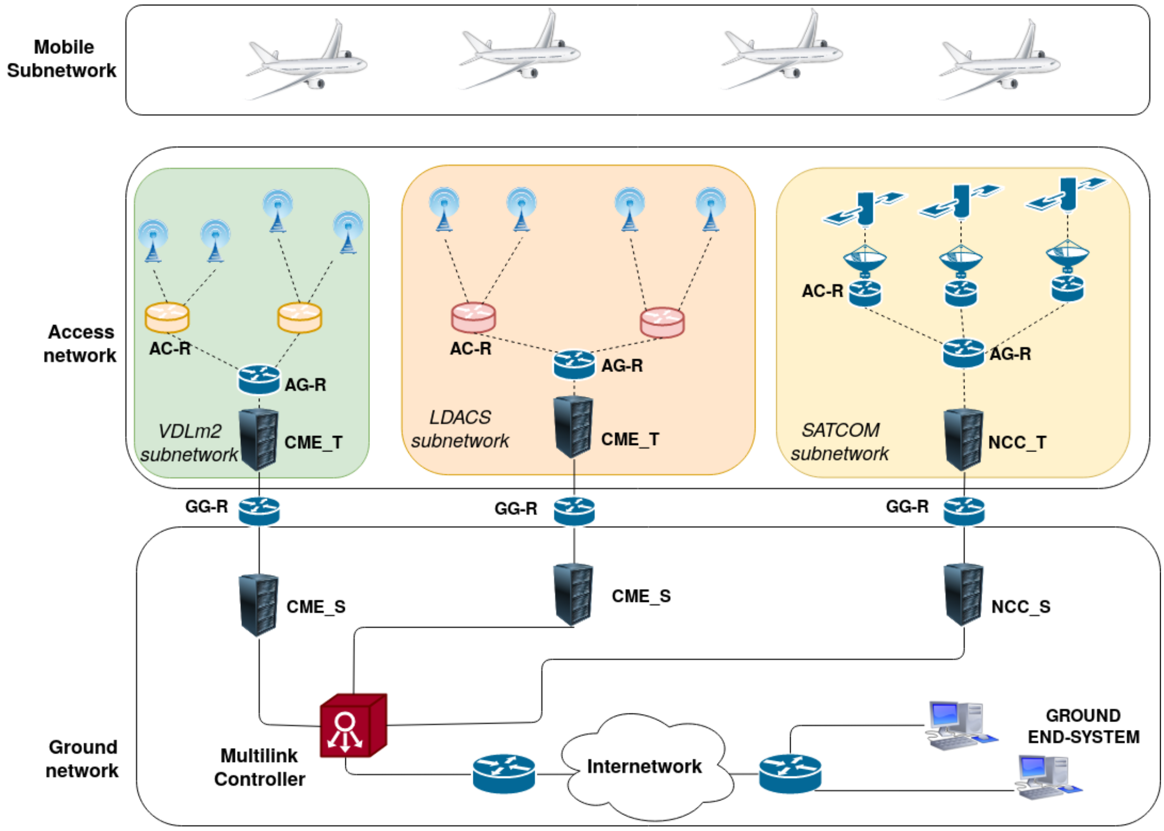


Figure 3.13: the ATN/IPS in the SAPIENT framework

The aircraft attachment can be performed by the solution we described in Chapter 2, though in the current version of the framework, the aircraft IP mobility is handled via tunneling mechanism at the ground station.

- the access network: is composed of three subnetworks: the VDLm2, the LDACS and the SATCOM subnetwork. The VDLm2 subnetwork has been implemented in the SAPIENT framework for this study as it will be one of the access network in the future ATN/IPS.

- the ground network: is in charge of connecting the previous subnetwork to the core ATN/IPS to enable the communication between the ground end-systems (referred as ATC and AOC end-systems here). The presence of a multilink controller is to allow to route the download traffic to any available links to the aircraft. Note that the multilink policy on the ground side might differ from the policy onboard the aircraft.

3.2 Aircraft

The aircraft subnetwork is shown in the Figure 3.14. The end-systems are linked to the onboard router through a switch. The *Pilot* end-system generates the safety application packets while the *Sapient* end-system has been implemented for research purpose. In this part, we are going to use only the Pilot end-system. The role of the onboard router is twofold: to forward the application packets to the ground entity destination using IP routing and the upcoming packets to the *Pilot* end-system. The download traffic is always routed through the *ethernet* interface, while the upload traffic is routed through the *Link Selector* interface. Then the *Link Selector* interface selects the best link to use according to the QoS required.

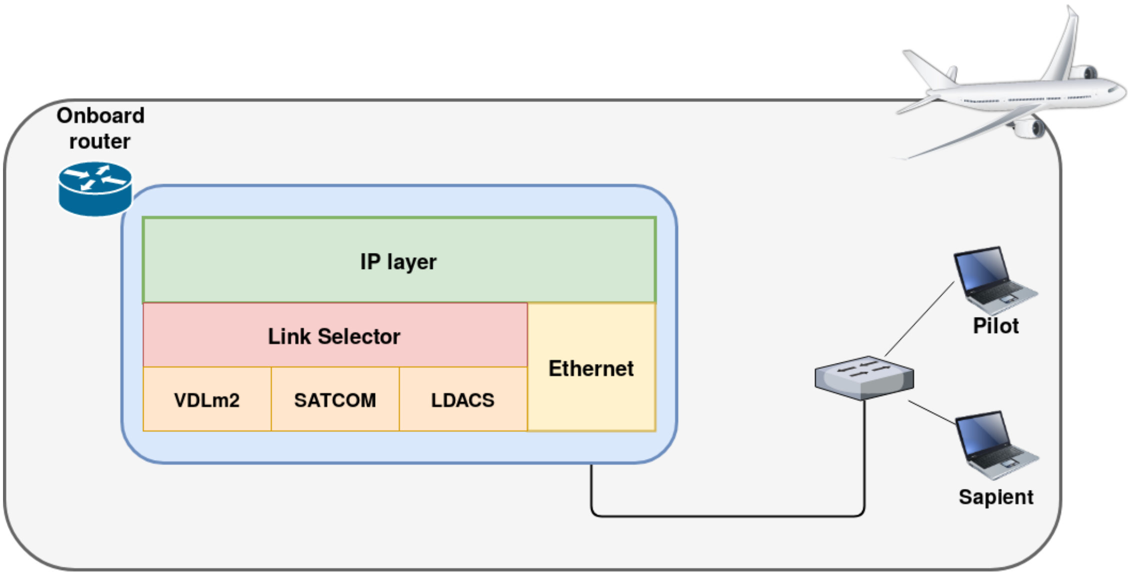


Figure 3.14: Aircraft model in the SAPIENT framework

3.3 Wireless Network Interface Controller (NIC)

The wireless Network Interface Controller (NIC) module, which is below the Link Selector in the Figure 3.14, is composed of 3 submodules as shown in the Figure 3.15. The *Layer 1* submodule implements the physical channel functions and set the parameters such as the frequency, the propagation delay, the signal transmission power and so on. Upon receiving a signal, the *Layer 1* computes the Signal-to-Noise (SNR) ratio and transmits the packet to the *Layer 2* submodule if the SNR is above a certain threshold (which is technology dependent). The *Layer 2* submodule performs the horizontal handover when it is necessary (for LDACS and VDLm2 technologies), meaning that on the aircraft side, it senses the neighboring base stations and attaches to the base station with the highest SNR ratio. Also, it manages the radio resources on the wireless link. Different resource management policies are implemented depending on the link technology. Finally, the *IP2L2* submodule interfaces the wireless NIC with the IP layer. When a packet is received from the the *Layer 2*, it is forwarded to the IP layer. When a packet is received from the IP layer, it retrieves the next hop's ID from the oracle. From the base station's side, the next hop is necessary an aircraft, which is the destination of the IP packet, so the next hop's ID is deduced from the IP destination address. From the aircraft's side, the next hop only depends on the aircraft which chooses which link to use, so the next hop ID is retrieved from the aircraft ID.

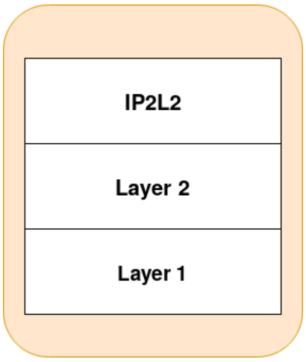


Figure 3.15: The generic wireless Network Interface Controller

3.4 Wireless access network

The wireless access network is composed of ground stations (GS) (plus satellites in the case of SATCOM), access routers (AC-R) and air-ground routers (AG-R) and the control entity X_T and X_S in the ground network (X being the Central Management Entity (CME) for cellular subnetwork and the Network Control Center (NCC) for satellite subnetwork). The GSs have the role of managing the radio resources for the aircraft connected to them and transmitting data packets to the aircraft and the control entity. The control entity X_T is responsible to tunnel the download traffic to the GSs attached to the aircraft and tunnel the upload traffic to the ground network. The X_S entity implemented in the ground network decapsulates and forwards the tunneled packets to the ground end-system.

3.5 Wireless access technologies

The wireless access technology has a direct impact on the delay of the packets, depending on the Medium Access Control (MAC). In the ATN/IPS, several link technologies are deployed and each one has its own MAC protocol. In this work, we consider two different MAC protocols that covers both the satellite and ground access networks in the ATN/IPS:

- VDLm2 technology: that uses a Carrier Sense Multiple Access (CSMA) p-persistent protocol to control the medium access. It is a decentralized protocol in which each node listens to the channel, and upon detecting a silence period, has a probability p of transmitting a packet. After $N1$ trials without success, the transmission is guaranteed. The VDLm2 has also a retransmission mechanism which is based on timer expiration: the receptor has to send back an acknowledgement after $T2$ seconds and if the sender does not received it within $T1$ seconds (with $T1 > T2$), the packet needs to be retransmitted, and the retransmission counter is increased by 1 and the timer $T1$ is increased as the channel may be congested. If the retransmission timer reaches the threshold $N2$, the VDLm2 link will be disconnected because the channel can no longer ensure the required QoS performances. The VDLm2, already in use for ground access network in the ATN/OSI, is expected to be compatible with the ATN/IPS, thus legitimating its evaluation.

- SATCOM and LDACS technologies: that use a centralized Time Division Multiple Access (TDMA) at the MAC layer. In this version of the TDMA protocol, the ground station acts as the central entity which allocates the timeslots to the users. In the LDACS system, the user's request takes one timeslot, before it can be scheduled, adding one extra timeslot delay. In the SATCOM system, the user doesn't need to explicitly request resources as each registered user is granted a certain throughput based on its contract with the SATCOM service provider, thus removing one timeslot delay. Besides, these systems manage three levels of priority, allowing to efficiently manage high priority packets such as safety critical aeronautical ones. The access network will be deployed in the future for the ATN/IPS to increase the available resource for new types of critical applications.

4 Performance assessments

In this section, the different approaches regarding the methods to assess the link quality based on the RTT delays retrieved from ICMP packets are evaluated in the SAPIENT framework. Our simulations are based on real data traffic: we used the data available on Eurocontrol depository [EUR], and we replayed the air traffic in the Maastricht region for the month February 2020, displayed in the Figure 3.16. Each of our simulation lasts for 24h, representing one day in February 2020.

4.1 Simulation scenarios

As a reminder, the goal of this work is to evaluate the link quality on different link technology through their used capacity rate. For the proof of our concept, we simulate the daily air traffic that covers a certain region, represented by one radio cell. Therefore, events such as handovers (vertical or horizontal) are not evaluated here. Besides, our evaluation scenario is based on two different radio link technologies, namely VDLm2 and LDACS. They have a different medium access control policy that may impact the end-to-end delay of the probes and therefore the results of our algorithm. We choose the Maastricht region which is one of the most dense region in Europe in terms of air traffic volume. Given the datalink traffic given in [RMS+14] and the peak instantaneous aircraft count (PIAC) in the Maastricht region, the cell's received throughput does not exceed 30% of the maximum capacity of a VDL cell and 10% of an LDACS cell. Therefore, we cannot detect any congestion in the radio cell for both of these link technologies. In consequence, as the number of aircraft in the cell cannot indefinitely growth, we arbitrary increase the data traffic by adding in parallel to the aeronautical safety application, a burst application on each aircraft to reach a higher percentage of the maximum channel capacity. For a VDLm2 cell, the maximum observed load is around 65%. Above this value, link disconnection, triggered by the LME (Link Management Entity) when too many retransmissions are necessary, may happen for some aircraft thus reducing the overall load. While for the LDACS cell, the maximum load can go up to 80%. The parameters of the burst application are presented in the Table 3.3.

	LDACS	VDLm2
Packet size (in Bytes)	uniform(12,484)	uniform(12,484)
talkspurt duration (in s)	exponential(110)	exponential(150)
silence duration (in s)	exponential(40)	exponential(20)
packetization interval (in s)	uniform(2,4)	uniform(20,25)

Table 3.3: Parameters of the burst application

The packet size is the same as the one specified in [RMS+14], where the inter arrival packet delay is shorter. The application emits N packets of size **Packet size** during a **talkspurt duration** interval, and then turns into a silent mode during a **silence duration** interval. The number N is equal to the integer part of the fraction $\frac{talkspurt\ duration}{packetization\ interval}$.

We then retrieve the information of the air traffic in the Europe region on the *Eurocontrol* website [EUR] and we filter the air traffic above the Maastricht region in February 2020. The Figure 3.16 shows the evolution of the number of aircraft during 24 hours in February 2020. The data show a certain pattern for the month of February 2020. Indeed, the traffic is relatively calm during the night and starts to increase in the morning until it reaches a peak at around midday, and then start to decrease afterwards. In consequence, we expect the link quality to follow the same pattern as the used capacity rate is correlated with the number of aircraft in the cell. This repetitive pattern justifies the use of supervised learning algorithms such as the ones we chose in the previous section. Indeed we will split the data we have into a training set and a testing set that show similar variations along the day.

Our active method, which will gather RTT delays information for the three algorithms mentioned previously, will add more traffic to the network, so we must ensure it does not represent a huge amount in proportion of the aeronautical safety data traffic. The total traffic we are taking into consideration in our scenario is detailed in the Table 3.4 and 3.5 (we compute the average throughput for all the traffic types by taking the average values of the packet per second (PPS) and the packet size). The data are given per aircraft except for the last column where we take into account the maximum load in a cell. By setting the ping interval at 20s and 60s for the LDACS and VDLm2 link respectively, we ensure that a small proportion of the bandwidth (3% and 6.8% for LDACS and VDLm2 respectively) is dedicated to our mechanism. The ping interval value is not specific to aeronautical network domains, and can be subject to modification in the future. These values will serve as a baseline for our study and has been chosen to achieve a good trade-off between the accuracy of the link evaluation model and its intrusion on the ATN/IPS.

Traffic type	PPS	packet size (B)	throughput (B/s)	% of band-width at PIAC
ATS	0.008	44	0.35	0.3
AOC	0.004	286	1.14	1
Burst	0.24	286	68.64	62
Ping	0.05	64	3.2	3

Table 3.4: LDACS scenario

Traffic type	PPS	packet size (B)	throughput (B/s)	% of band-width at PIAC
ATS	0.008	44	0.35	2
AOC	0.004	286	1.14	7.2
Burst	0.04	286	11.44	72.6
Ping	0.017	64	1.08	6.8

Table 3.5: VDLm2 scenario

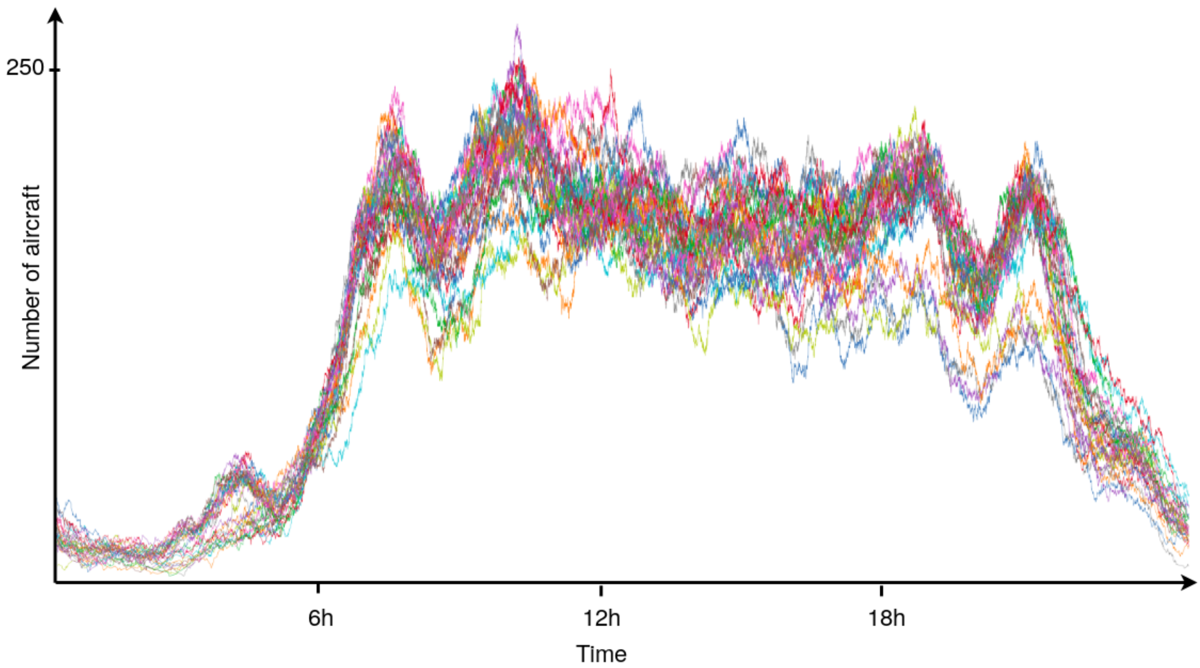


Figure 3.16: Air traffic in February 2020 above the Maastricht region

4.2 Threshold based

The first method we propose in 2.3.1, is assessed based on the scenario described in 4.1. We first explain how we choose the two features and the corresponding thresholds for both the VDLm2 and LDACS link technologies. We then apply our threshold-based model based on the selection of 2 features to the aeronautical case study. With this method, we want to predict 3 states of the radio link : GOOD, MEDIUM and BAD, referring to the level of congestion (BAD being a very congested link).

4.2.1 Features selection

As said earlier, most of the end-to-end delay is due to the delay induced by the radio link. Besides, the two wireless link technologies, detailed in the section 3.5, present different characteristics, so we decide to treat them separately.

VDLm2 case scenario

The VDLm2 link technology is based on a random algorithm (CSMA p-persistent), with a probability to emit $p = 13/256$ ($\simeq 0.05$). It means that, when a node is listening to an idle channel, it has a 5% chance to effectively transmit its packets. Between two trials, it must wait TM1 = 4.5 ms. So if we consider a non congested link, the VDLm2 layer is accounted for $2 * TM1 * 1/0.05 = 180$ms of the RTT in average. After $M1 = 135$ unsuccessful trials, the transmission in guaranteed, so in the the normal case the maximum delay induced by the VDLm2 layer for a RTT is up to $2*135*4.5 = 1215$ms. So for the VDLm2 case scenario, we are taking the RTT value as the first feature, and concerning the second one, we will study the performances of different features that represent the variations of the RTT such as: the mean, the exponential moving average, and the rolling standard deviation. The mapping of our algorithm can be represented as illustrated in the Figure 3.17 with the average_rtt as a second feature. The algorithm only needs 6 parameters : $feat1_{GOOD}^{max}$, $feat2_{GOOD}^{max}$, $feat1_{MEDIUM}^{max}$, $feat2_{MEDIUM}^{max}$, $feat1_{BAD}^{max}$, $feat2_{BAD}^{max}$. This algorithm is slightly different from the one presented in the Figure 3.9 because for the VDLm2 link, the RTT value is more volatile due to the MAC layer procedure. Indeed, having a high RTT value (feature 1) does not correctly define the state of the link, as we have seen that in the normal case, the RTT value can range from milliseconds up to one second.

LDACS case scenario

The LDACS link technology is based on timeslots. In consequence when the state of the link is GOOD (i.e in a normal), an aircraft requesting a resource to the ground station will automatically get served in the next timeslot. Let's call T the timeslot when the packet is arriving at the aircraft MAC layer. So the packet is emitted at the timeslot $T+1$, which leads to a delay between 1 and 2 timeslots. When the response comes back at the ground station, less

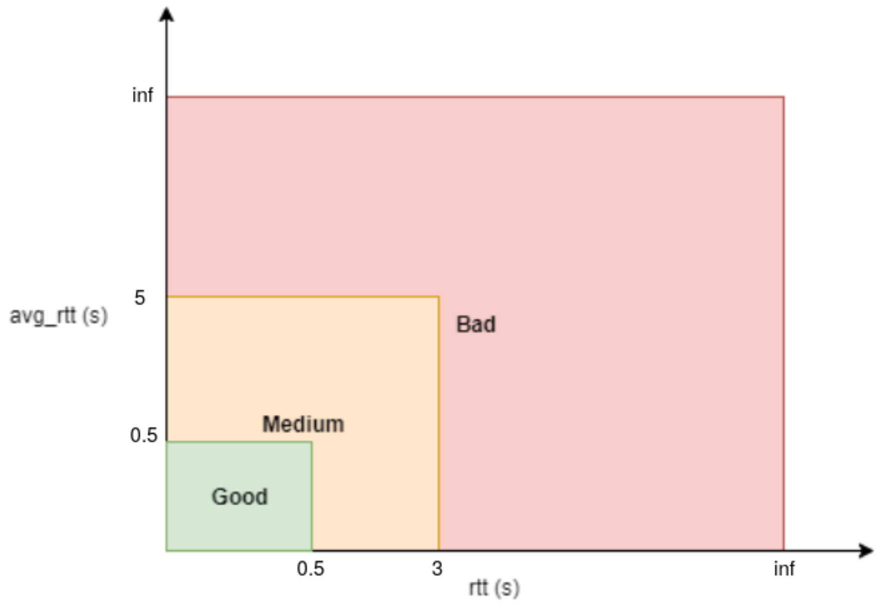


Figure 3.17: VDL threshold based algorithm

than one timeslot has occurred. Then, the ground station allocates the timeslot for this packet in the next timeslot $T + 2$, meaning that the round trip delay is at minimum of 2 timeslots (120ms) and the maximum delay in that case is of 3 timeslots (180ms). The RTT in the normal case is summarized in the Figure 3.18. When the link is more congested, the resource to send the packet may be allocated after several timesteps, leading to a overall increase of the RTT values. Based on this phenomenon, we create one feature called the the 1st non-zero quantile (1NZQTH). To compute the 1NZQTH, we re-scale the RTT with a score function σ as follows:

$$\sigma(RTT) = \begin{cases} \frac{RTT(ms)-180}{60} & \text{if } RTT(ms) > 180 \\ 0 & \text{else.} \end{cases} \tag{3.9}$$

The score function σ detects the congestion when it is a strictly positive. The 1NZQTH is based on the past history of the RTT. Given a window of the past RTTs, the 1NZQTH computes the first quantile with a non zero σ value. The 1NZQTH is therefore between the interval [1;100]. A smaller value of the 1NZQTH means a higher congestion level as it means that the past history contains a lot of RTT higher than 180ms. For instance, a 1NZQTH of 90 means that 10% of the past RTTs (in a certain window) are over 180ms, while a value of 50 means that 50% of the RTTs go over 180ms.

4.2.2 Validation on the air traffic dataset

We assess the performances of the different selected features based on the scenarios defined in 4.1. The principal criterium is the precision of the algorithm and particularly the precision for the BAD link state.

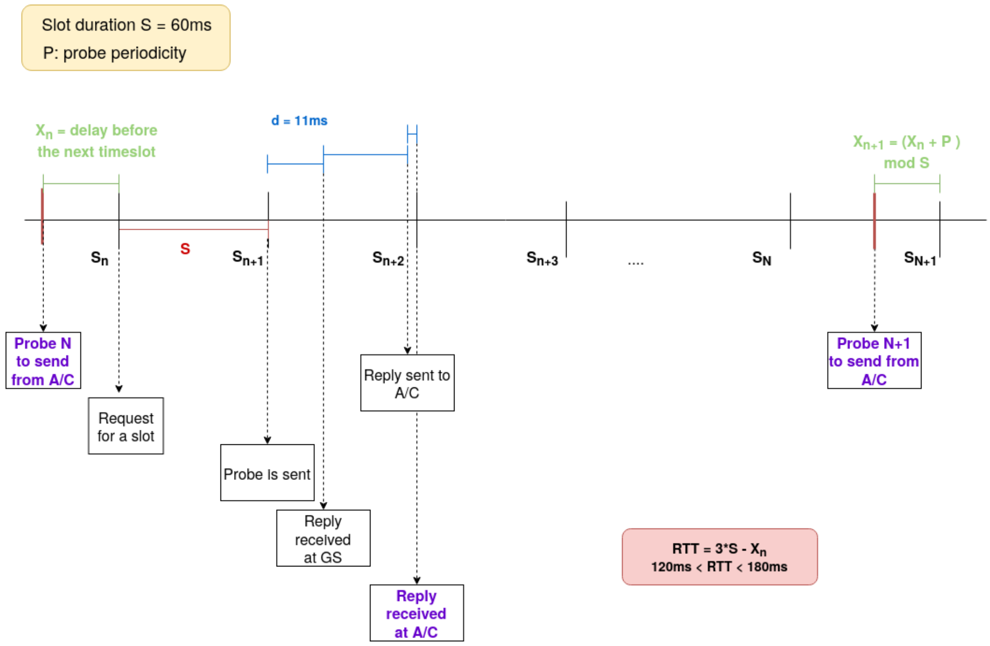


Figure 3.18: Delay study for LDACS link in a normal state

states	feature 1 max(s)	feature 2 max (s)
GOOD	0.5	0.5
MEDIUM	5	3
BAD	∞	∞

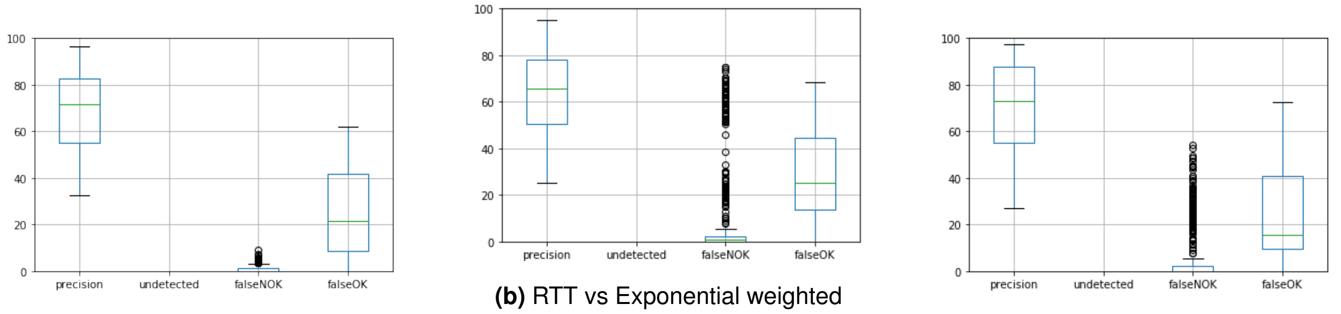
Table 3.6: Threshold based algorithm parameters for the VDLm2 link

VDLm2 case scenario

For the VDLm2 case scenario, the 3 states are represented as follows: {GOOD = 0-20%, MEDIUM = 20-50%, BAD = 50-100%}. The distribution is not equal because the VDLm2 link performances degrade faster with the level of congestion. We only need to specify 6 parameters for the algorithm : the maximum values for each feature per class. The global performances of the algorithm are shown in the Figure 3.19. Among the methods presented in Figure 3.19a and 3.19b, which use the average method as a second feature, the average RTT demonstrates better performances for all the metrics, and particularly with 10% increase in precision. However, the method with the Rolling standard deviation (Figure 3.19c) is slightly better than the average RTT method (2% more accurate), but at a cost of more false NOK errors.

LDACS case scenario

For the LDACS case scenario, the classes are represented as follows: {GOOD = 0-30%, MEDIUM = 30-60%, BAD = 60-100%}. For this algorithm, we need to specify 12 parameters, 4 for each class. The feature 1 is either the



(a) RTT vs Average RTT **(b)** RTT vs Exponential weighted average (N=10) **(c)** RTT vs Rolling standard deviation

Figure 3.19: Performances of the threshold based algorithm for the VDLm2 link

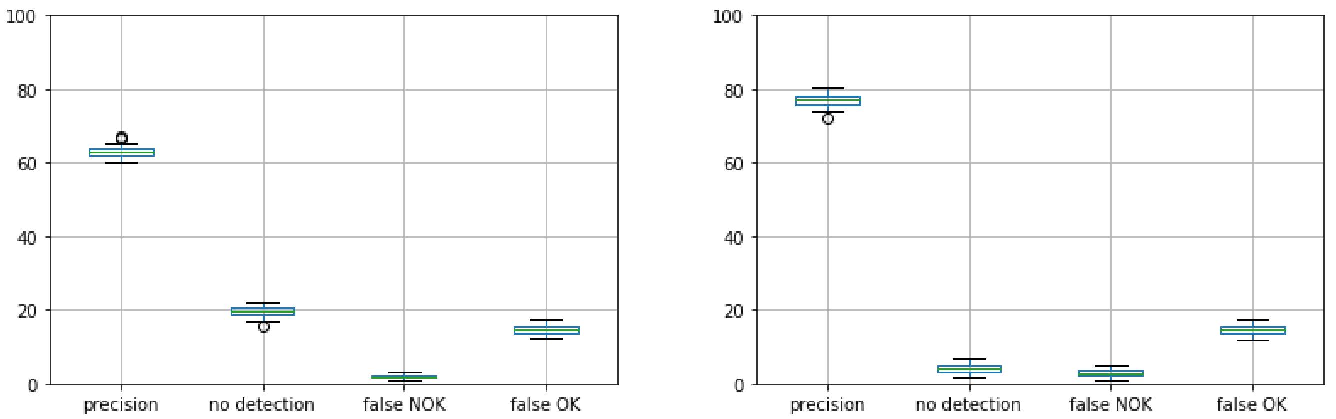
states	feature 1 min (in s)	feature 1 max (in s)	feature 2 min	feature 2 max
GOOD	0	0.185	87	100
MEDIUM	0.185	0.3	8	87
BAD	0.3	∞	0	8

Table 3.7: LDACS threshold based algorithm parameter values

RTT or the average RTT and the feature 2 is the 1NZQTH. The Table 3.7 gathers all the parameter values.

The results are shown in the Figure 3.20 for each of the solutions. Clearly, the solution considering the average RTT shows a better performance compared to the one with the RTT, with a almost 20% increase in the precision. Also, it presents a lower miss detection rate (about 15% lower) with a same false NOK and false OK rate. The false NOK rate takes into account the errors of the algorithm that can lead to a huge misinterpretation of the channel state. Those errors concern the false detection of the BAD channel quality. The false OK rate gather all the other errors which are more acceptable such as predicting a MEDIUM quality instead of a GOOD quality and reversely.

In conclusion, with a simple method that does not require much computational power, we are able to evaluate the quality of the link with a accuracy of 75-80% in average for both LDACS and VDLm2 links. However, this algorithm may make a lot on inaccurate estimations in the case of non-deterministic link technologies such as with the VDLm2



(a) RTT vs 1NZQTH **(b)** Average RTT vs 1NZQTH

Figure 3.20: Performances of the threshold based algorithm for the LDACS link

link, where the false OK metric is more spread out.

4.3 The probabilistic approach with the HMM

The second method we implement is the probabilistic approach, that has been described in the section 2.3.2. For both the LDACS and VDLm2 case scenario, we trained the HMM based on 80% of the air traffic data to compute the state probability matrix A and the emission matrix B. These matrices are then used to make the link quality prediction over a single step and five steps.

4.3.1 VDLm2 case scenario

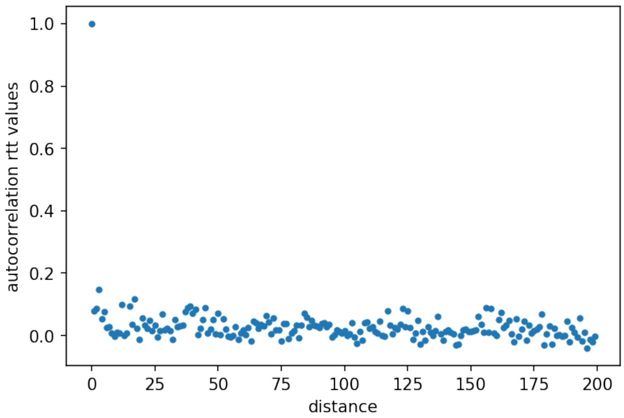
We first set the parameters of the model as shown in the Table 3.8. We sample the values of the RTTs with a shorter step for small values as most of the time, the RTT delay is expected to be low, reflecting a good link quality.

$\mathcal{N}$ states	[GOOD, MEDIUM, BAD]
$\mathcal{O}$ observations	0.01, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.8, 0.9, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 10, 20, 30, 40, 50
matrix $\mathcal{A}$	$\begin{pmatrix} 9.594 \times 10^{-1} & 4.055 \times 10^{-2} & 5.196 \times 10^{-5} \\ 3.492 \times 10^{-2} & 8.2156 \times 10^{-1} & 1.435 \times 10^{-1} \\ 1.904 \times 10^{-4} & 3.9918 \times 10^{-1} & 6.0063 \times 10^{-1} \end{pmatrix}$
matrix $\mathcal{B}^T$	$10^{-2} \times \begin{pmatrix} 0 & 0 & 0 \\ 4.44 & 1.754 & 1.225 \\ 15.4 & 7.511 & 5.390 \\ 17.5 & 9.920 & 7.530 \\ 15.7 & 10.26 & 8.122 \\ 12.7 & 9.669 & 7.970 \\ 9.46 & 8.464 & 7.349 \\ 6.80 & 7.288 & 6.376 \\ 4.78 & 6.128 & 5.822 \\ 3.36 & 4.928 & 4.869 \\ 2.34 & 4.121 & 4.241 \\ 1.57 & 3.329 & 3.489 \\ 1.11 & 2.678 & 2.885 \\ 7.410 \times 10^{-2} & 2.136 & 2.531 \\ 8.579 \times 10^{-2} & 2.985 & 3.683 \\ 0.356 & 1.874 & 2.448 \\ 0.166 & 1.167 & 1.731 \\ 9.111 \times 10^{-2} & 1.590 & 3.083 \\ 2.803 \times 10^{-3} & 0.104 & 0.404 \\ 7.476 \times 10^{-3} & 5.637 \times 10^{-3} & 7.504 \times 10^{-2} \\ 0.481 & 1.329 \times 10^{-2} & 2.128 \times 10^{-2} \\ 0.102 & 0.717 & 0.104 \\ 0.677 & 2.607 & 1.120 \\ 0.218 & 3.553 & 2.667 \\ 4.158 \times 10^{-2} & 3.017 & 3.520 \\ 0.125 & 3.317 & 9.790 \\ 7.475 \times 10^{-3} & 0.760 & 2.832 \\ 0.000 & 5.067 \times 10^{-2} & 0.466 \\ 0.000 & 3.624 \times 10^{-3} & 0.132 \\ 0.000 & 8.053 \times 10^{-4} & 123 \end{pmatrix}$

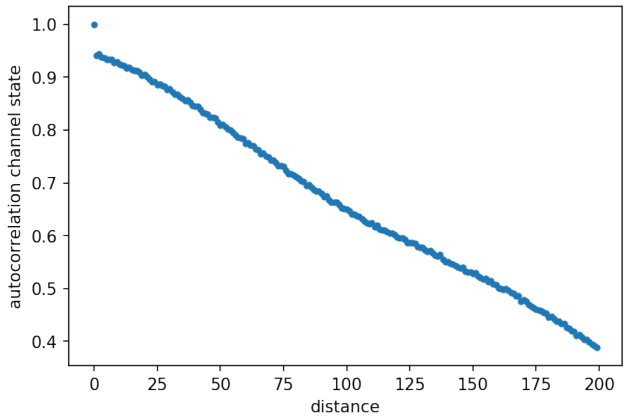
Table 3.8: the HMM parameters for the VDLm2 case scenario

Then we evaluate the algorithm (3.3) on the test set, by giving it the first RTT measure as well as the initial state which is the state GOOD. After running the algorithm during the whole simulation time, the output always predicts the state GOOD. One possible explanation of this behavior is the data distribution, and the correlation between the different data. We compare the RTT signal with the link state signal using the cross-correlation formula given for 2 stochastic processes X and Y by the equation 3.10 as well as the autocorrelation of the two signals.

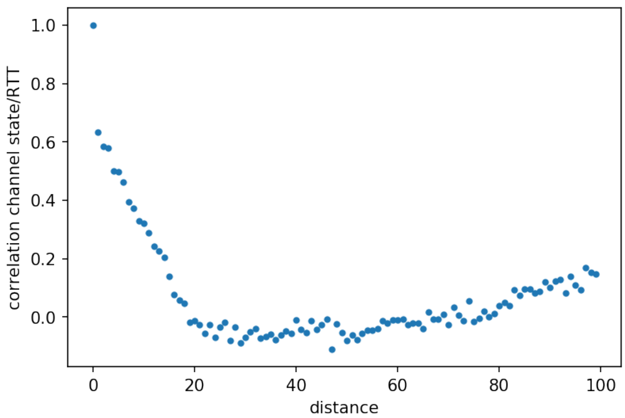
$$\forall\tau \quad in \quad \mathbb{N}, \mathcal{R}_{XY}(\tau) = \mathbb{E}[X_t\overline{Y_{t+\tau}}] = \sum_{k=0}^{\infty} x[\tau] \times y[k+\tau] \tag{3.10}$$



(a) RTT autocorrelation



(b) Channel state autocorrelation



(c) Correlation between the RTT and the channel state

Figure 3.21: Training dataset correlations for the VDLm2 case scenario

The Figure 3.21b shows that the link quality autocorrelation does not decrease as fast as it should to respect the Markov property saying that the hidden state only depends on the last state. Indeed, we can see that the correlation is still high (> 0.9) for a distance of 20 steps, so the hidden state at time t is strongly related to previous hidden states. Also, the Figure 3.21c shows a higher decrease slope but still, for a distance of 10, the correlation between the RTT and the link state is observable.

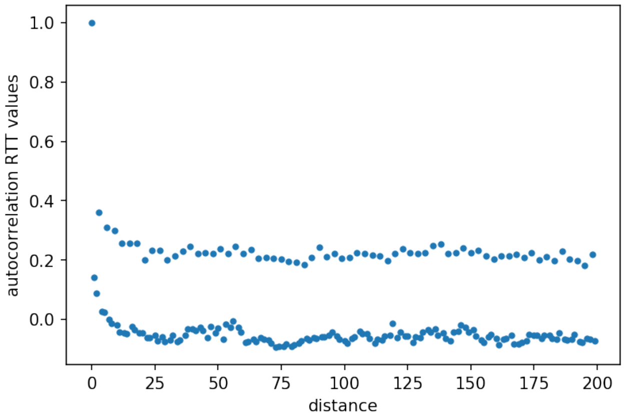
4.3.2 LDACS case scenario

We first set the parameters of the model as shown in the Table 3.9. We sample the RTT values based on the multiples of the LDACS timeslot (60ms). Likewise, the prediction of the HMM model is completely wrong and is always estimating a good channel capacity. Looking at the correlations of the training dataset in the Figure 3.22, the channel state autocorrelation is less pronounced but still it doesn't decrease as fast as expected for a Markov model, with a value superior than 0.35 for all the distance below 200. Like the VDLm2 case scenario, this could explained why the HMM cannot correctly estimate the link quality. However, the output dependence hypothesis can be validated based on the Figure 3.22c. Indeed, the correlation between the RTT observations and the link state is not significant with an average value over the distance 0.08.

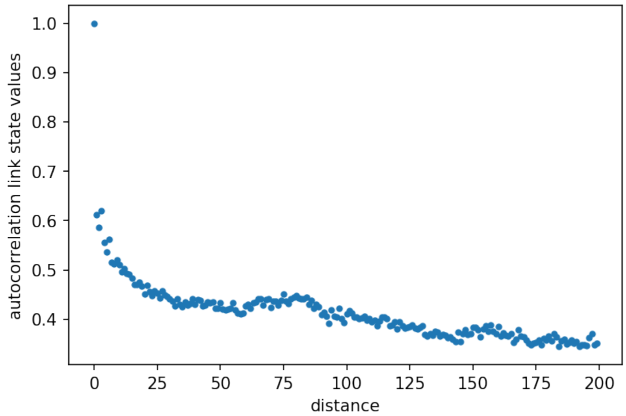
$\mathcal{N}$ states	[GOOD, MEDIUM, BAD]
$\mathcal{O}$ observations	0, 0.2, 0.32, 0.44, 0.56, 0.72, 0.84, 0.96, 1.08, 1.32, 1.56, 2.04
matrix $\mathcal{A}$	$\begin{pmatrix} 9.935 \times 10^{-1} & 6.486 \times 10^{-3} & 0 \\ 4.703 \times 10^{-3} & 9.869 \times 10^{-1} & 8.380 \times 10^{-1} \\ 0 & 2.369 \times 10^{-2} & 9.763 \times 10^{-1} \end{pmatrix}$
matrix $\mathcal{B}^T$	$10^{-2} \times \begin{pmatrix} 0 & 0 & 0 \\ 98.2 & 8.55 & 8.08 \\ 1.47 & 11.1 & 13.5 \\ 0.23 & 2.27 & 3.43 \\ 6.321 \times 10^{-2} & 0.667 & 1.261 \\ 2.764 \times 10^{-2} & 0.268 & 0.638 \\ 4.049 \times 10^{-3} & 6.255 \times 10^{-2} & 0.188 \\ 1.584 \times 10^{-3} & 2.655 \times 10^{-2} & 9.784 \times 10^{-2} \\ 1.056 \times 10^{-3} & 1.008 \times 10^{-2} & 4.51 \times 10^{-2} \\ 3.521 \times 10^{-4} & 9.192 \times 10^{-3} & 3.574 \times 10^{-2} \\ 0 & 2.170 \times 10^{-3} & 1.047 \times 10^{-2} \\ 0 & 1.659 \times 10^{-3} & 2.888 \times 10^{-3} \end{pmatrix}$

Table 3.9: the HMM parameters for the LDACS case scenario

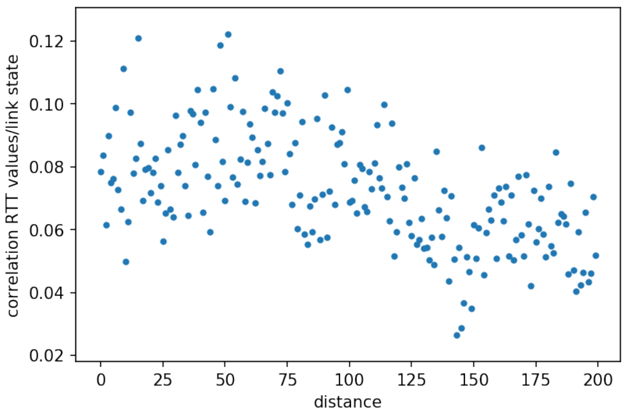
In conclusion, the HMM method investigated in our case scenarios, is not suited for estimating and predicting the link quality. Indeed, the model is too simple and cannot deal with the highly correlated link state, as the HMM is only good at predicting the future state of the link based on the previous state observation. However, in our case scenario, the link quality for both the LDACS and the VDLm2, present a high autocorrelation, indicating that a future link state depends on previous link states. With a single step prediction and a 5 steps prediction, the algorithm is not able to detect a link state switching from a GOOD to a MEDIUM state.



(a) RTT autocorrelation



(b) Channel state autocorrelation



(c) Correlation between the RTT and the channel state

Figure 3.22: Training dataset correlations for the LDACS case scenario

4.4 The machine learning method: LSTM

In this part, we assess the performances of a LSTM network for the link quality prediction. As mentioned above, among the machine learning methods, LSTM is particularly well suited for analysing time series data, such as our history of past RTT delays, and predict the future link quality.

We first explain how we trained our LSTM neural network to perform link quality estimation and prediction. The SAPIENT framework, in which we run our simulations, helps us obtain the true channel used capacity rate at each time. So, we are using a supervised learning method to train our deep learning algorithm as the labels for the training step is directly observable. We split our dataset as follows: the training set is composed of 90% of the data, while the remaining 10% is used for the model validation. Given the history of T_x past RTT measures, the goal is to predict the future states of the link.

4.4.1 Comparison with the threshold based-algorithm

First, we will compare the performances of the LSTM network to the threshold based algorithm to predict the next future state. The input vector $X_{<T_x>}$ is composed of T_x RTT past values, and the output vector is Y, representing the link quality. Y is here a label, which can take a value between $N = \{0, 1, 2\}$ as for the threshold based algorithm. The structure of our network is illustrated in the Figure 3.23. The model parameters are :

- initial learning rate lr:
- the optimizer : the algorithm to tune the learning rate to learn faster. We choose the Adam optimizer.
- N hidden states: the number of neurons inside the LSTM cell.
- rate : the rate of the Dropout layer, that can prevent from overfitting the training dataset.
- the loss function : the function defined to compute the gradients during the training. For the multi classification problem, the common metric is the *sparse categorical crossentropy*: the lower it is the better.
- the evaluation metric : the metric to evaluate the model during the training and the validation phase. For this problem, we choose the *sparse categorical accuracy*: the more it is close to 1 the better.

The training is realized with the mini-batch technique with a mini-batch size of 32, i.e the neural network takes 32 random input data per epoch to compute the loss function. The mini-batch is used in general to accelerate the training process.

VDLm2 case scenario

We chose the last model in the Table 3.10, which gives us a good trade off in terms of training loss and metric evaluation, and also has the advantage of having few number of hidden states. The classification results on the

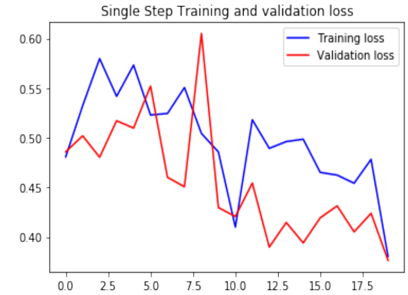
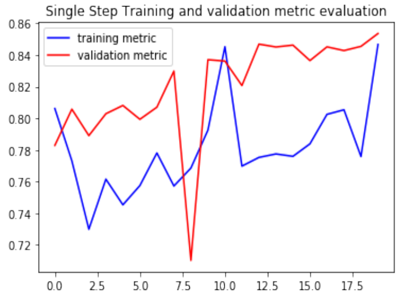
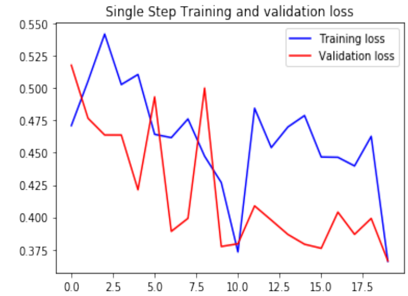
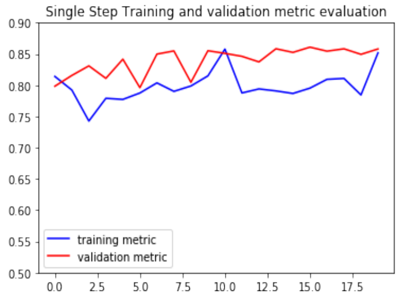
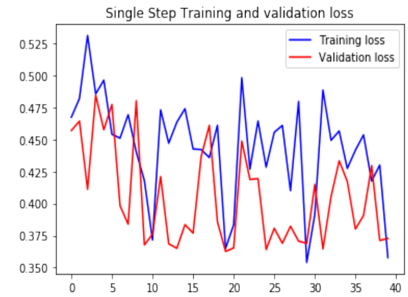
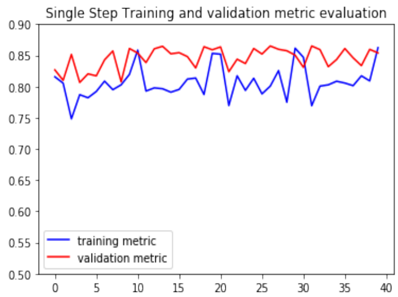
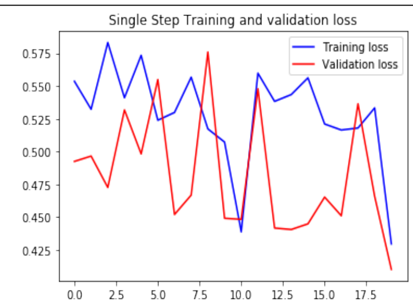
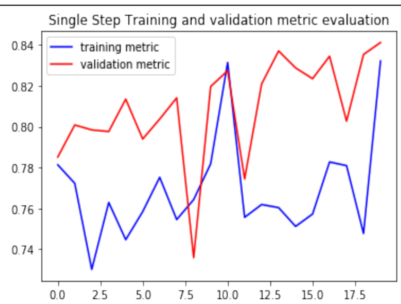
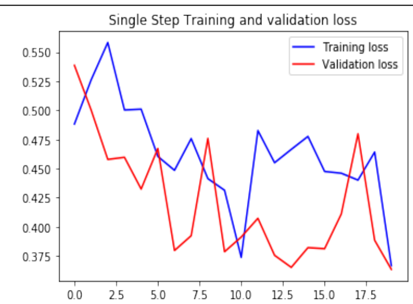
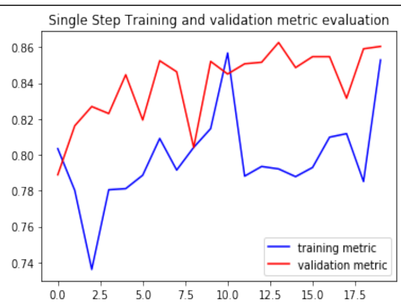
<table>
<tr><th>1earning rate lr</th><th>N hidden states</th><th>Training Loss</th><th>Evaluation metric</th></tr>
<tr><td>0.001</td><td>100</td><td>
</td><td>
</td></tr>
<tr><td>0.005</td><td>100</td><td>
</td><td>
</td></tr>
<tr><td>0.01</td><td>100</td><td>
</td><td>
</td></tr>
<tr><td>0.001</td><td>20</td><td>
</td><td>
</td></tr>
<tr><td>0.01</td><td>20</td><td>
</td><td>
</td></tr>
</table>

Table 3.10: LSTM neural network training for the multi classification problem for the VDLm2 link evaluation

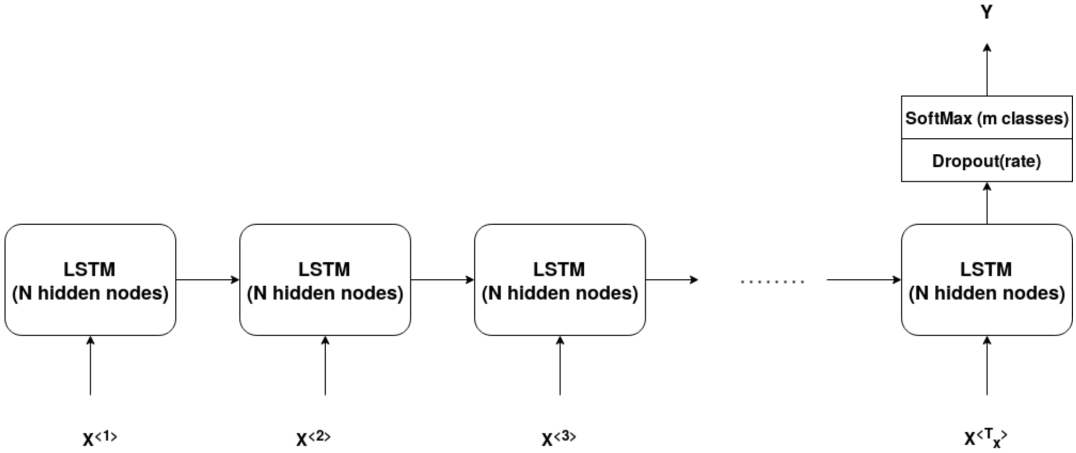


Figure 3.23: The LSTM network for the link quality prediction taken as a classification problem

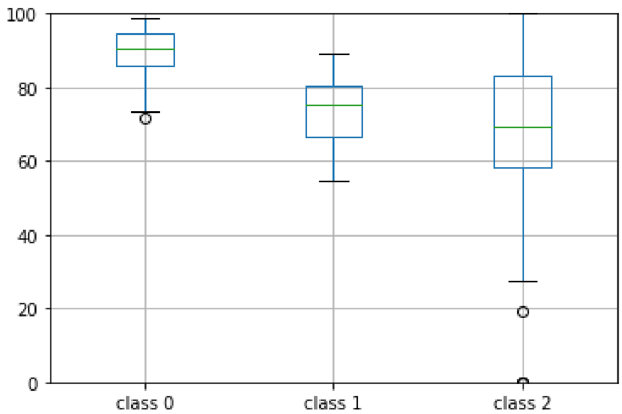
validation dataset of this model is given in the Figure 3.24 (in percentage %). Overall, the algorithm is very accurate with a global accuracy close to 80%. The Figure 3.24a highlights the precision per class, and shows the worst performance (70%) for the class 2 (BAD link), which can be explained by the few input elements of this class in the training, although we perform data augmentation to have more samples of the class 2 in our training set. The data augmentation consists here in replicating the same elements in the training set. While looking at the recall score (in the Figure 3.24b), which demonstrates the percentage of the true positive samples found by the algorithm among the total positives samples. The recall score is very satisfying for the class 0 and 1, with a score higher than 90%. However, it is very low for the class 2, meaning that the neural network struggles to identify all the class 2 samples. For the same reason, we think that the neural network has not seen enough of these class 2 samples to correctly recognize them. The F1 score (Figure 3.24c) is a metric that is used to represent both the precision and the recall at the same time. We also plot the false NOK and false OK metric, which has been defined previously. Regarding these two metrics, the neural network is doing fine with a score less than 15%.

Comparing to the threshold-based algorithm performances (Figure 3.19c), the overall results are less spread out but in average, there is not a huge gain in average precision with respectively 78% and 76% for the LSTM and the threshold-based algorithm. The LSTM algorithm tends to be more accurate with the False OK metric (10% compared to 18%), but with a cost of a degradation in the False NOK metric (14% compared to 5% on average).

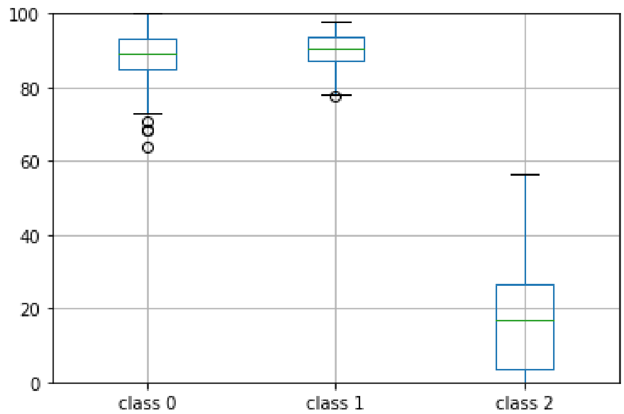
LDACS case scenario

For the LDACS case scenario, we chose the last model in the Table 3.11, as it presents the same evaluation metric but with less hidden states, thus implying less computational cost. For this case, we change the training set by taking 95% of the global data. Also, we perform data augmentation on the class 2 for our training set, as the class 2 only represents 15% of our training data. In the end, our training is split according to the Table 3.12.

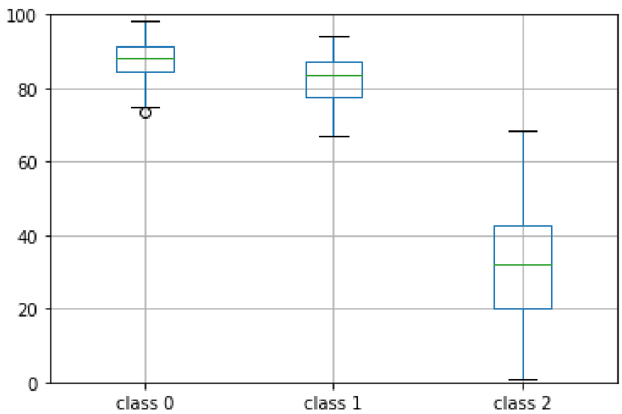
The data augmentation helps us achieve a global good precision with almost 80%, and with a precision by class



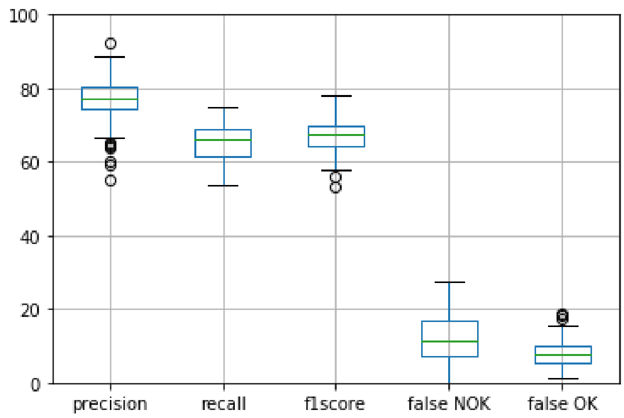
(a) Precision per class



(b) Recall per class



(c) F1score per class



(d) Global performances

Figure 3.24: Performances of the LSTM neural network for the VDLm2 link for the classification problem

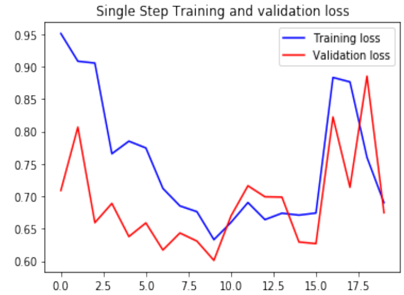
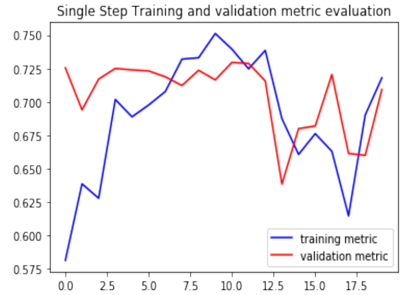
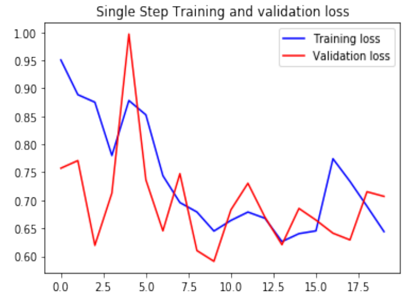
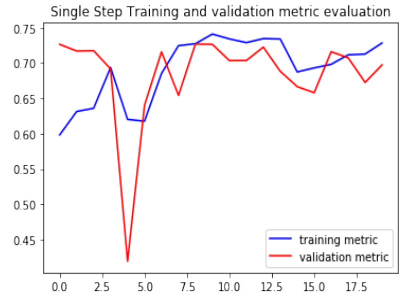
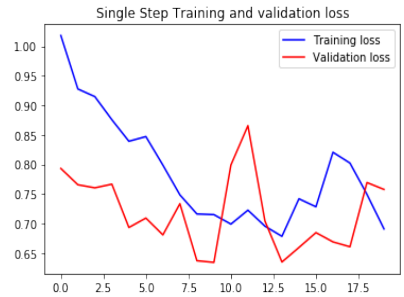
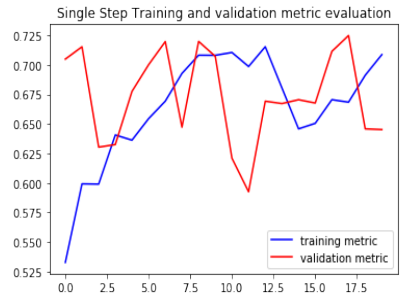
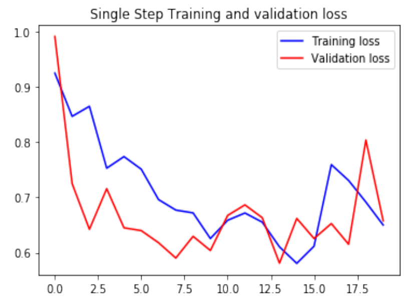
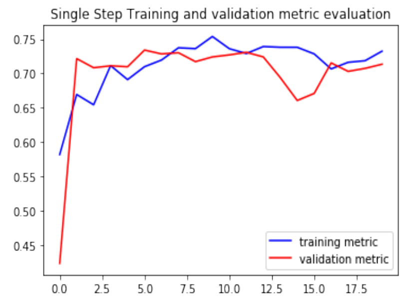
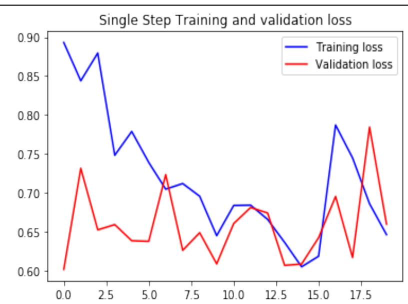
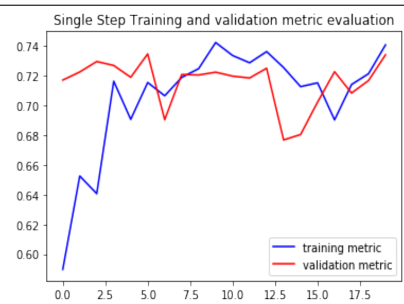
<table>
<tr><th>1earning rate lr</th><th>N hidden states</th><th>Training Loss</th><th>Evaluation metric</th></tr>
<tr><td>0.01</td><td>30</td><td></td><td></td></tr>
<tr><td>0.001</td><td>30</td><td></td><td></td></tr>
<tr><td>0.0001</td><td>30</td><td></td><td></td></tr>
<tr><td>0.01</td><td>60</td><td></td><td></td></tr>
<tr><td>0.01</td><td>200</td><td></td><td></td></tr>
</table>

Table 3.11: LSTM neural network training for the multiclassification problem for the LDACS link (with data augmentation)

Class	Number of samples	Repartition
Good (0)	739388	29.8%
Medium (1)	1062806	42.9%
Bad (2)	676714	27.3%

Table 3.12: Training set for the training over a LDACS link

higher than 70% (Figure 3.25a). The global performances of the neural network in the evaluation set are slightly lower than for the VDLm2 case scenario with a gobal recall and F1 score less than 60% (Figure 3.25). Likewise, the class 2 achieves the worst performances among the 3 classes, particularly for the recall and f1 score (Figure 3.25b and 3.25c). However, this does not impact significantly the global results as the class 2 data are less present in the evaluation set (representing only 16% of the data in the evaluation set). In addition, the metric false NOK and false OK are not exceeding 20%, which is a good result like in the VDLm2 case scenario.

Comparing the results to the threshold-based algorithm (Figure 3.20b), the precision metric is lower with an average of 70% compared to 78%. Concerning the error metrics, the LSTM is less accurate (18% compared to 4%) for the False NOK and more accurate for the False OK metric (15% compared to 17%). Like for the VDLm2 scenario, the LSTM network tends to favor the False OK errors compared to the False NOK ones.

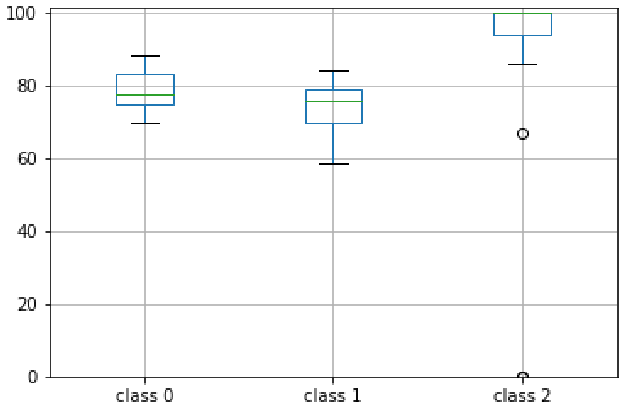
4.4.2 Increasing the number of classes

So far, we are able to classify the states of the link among 3 classes: GOOD, MEDIUM, BAD, which is already better than the current link status implemented in the ACARS router for the previous aeronautical networks (Chapter 1.1.3) that only states whether a link is UP or DOWN (meaning 2 states only). However, compared to the threshold based algorithm where we have limited input features and parameters for the algorithm, the LSTM neural network is capable of computing complex functions to recognize several classes. Therefore, we test out the LSTM neural network to classify among $m = 5$ classes. The more classes we can get, the more information we will be able to transmit to the multilink decision algorithm so that it will have a better image of the different link quality. To do so, in the neural network architecture in the Figure 3.23, we set the parameter of the Softmax layer accordingly, and test out different training setups.

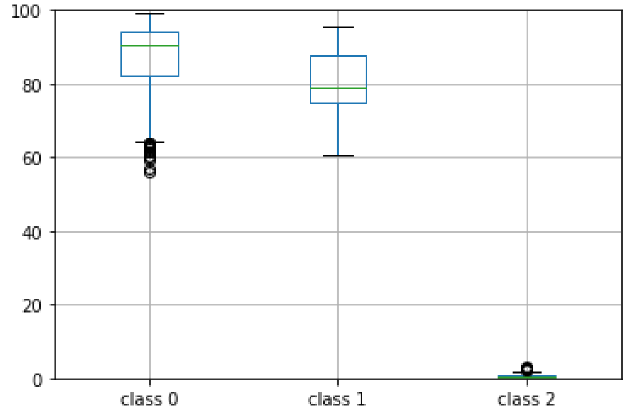
VDLm2 case scenario

The new classes are represented by their channel occupancy interval as follows: class 0= 0-15%, class 1= 15-30%, class 2= 30-45%, class 3= 45-60%, class 4= 60-100%.

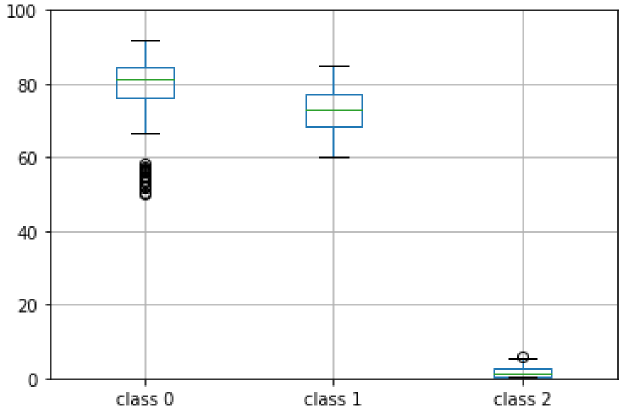
From the table 3.13, we chose the neural network with $lr = 0.01$ and $N = 50$ (note that we need more hidden states compared to the case with 3 classes), but all of them look similar during the training period. The performances on the validation set are presented in the Figure 3.26. For the precision metric, all the classes have more than 60% except the class 1, with an average precision of 40%, which is still better than the random guessing (25% in the



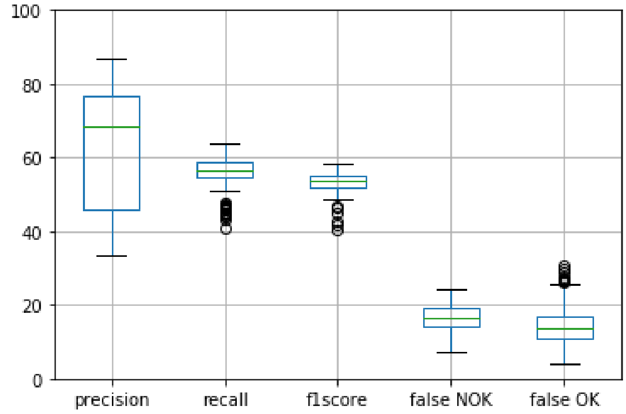
(a) Precision per class



(b) Recall per class



(c) F1score per class



(d) Global performances

Figure 3.25: Performances of the LSTM neural network for the LDACS link for the classification problem

case of 4 classes). Compared with the previous VDLm2 case with 3 classes, the global metrics are lower with respectively 63%, 44% and 56% in average for the precision, recall and f1 score. So the LSTM neural network with this kind of architecture is not well suited when the number of classes increases, at least for the VDLm2 case scenario.

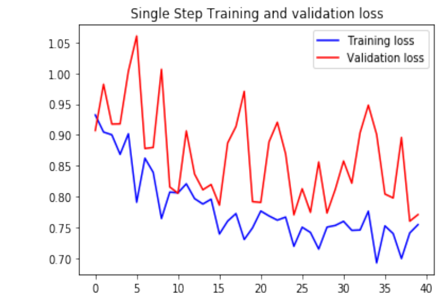
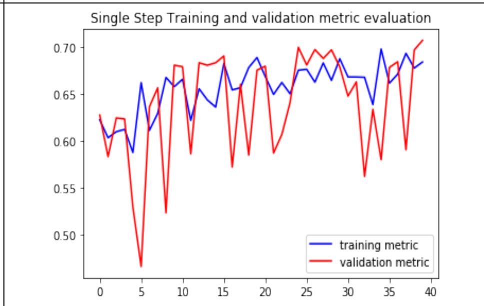
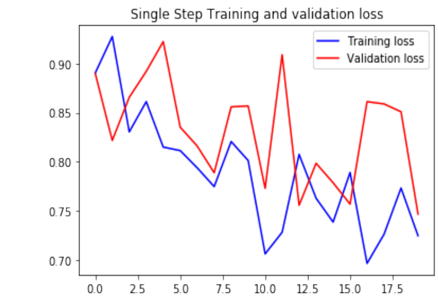
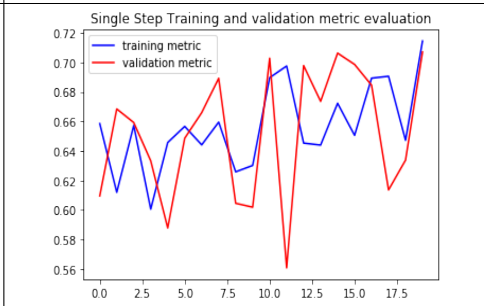
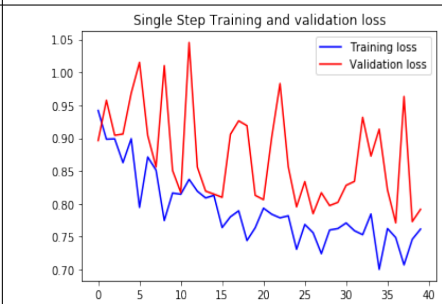
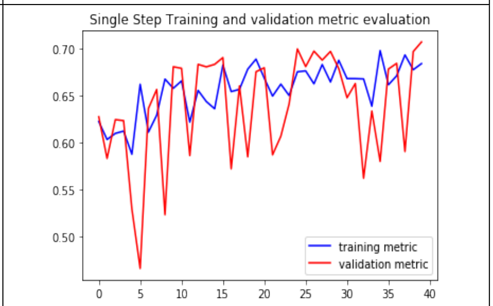
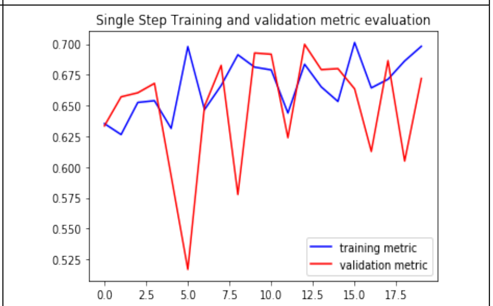
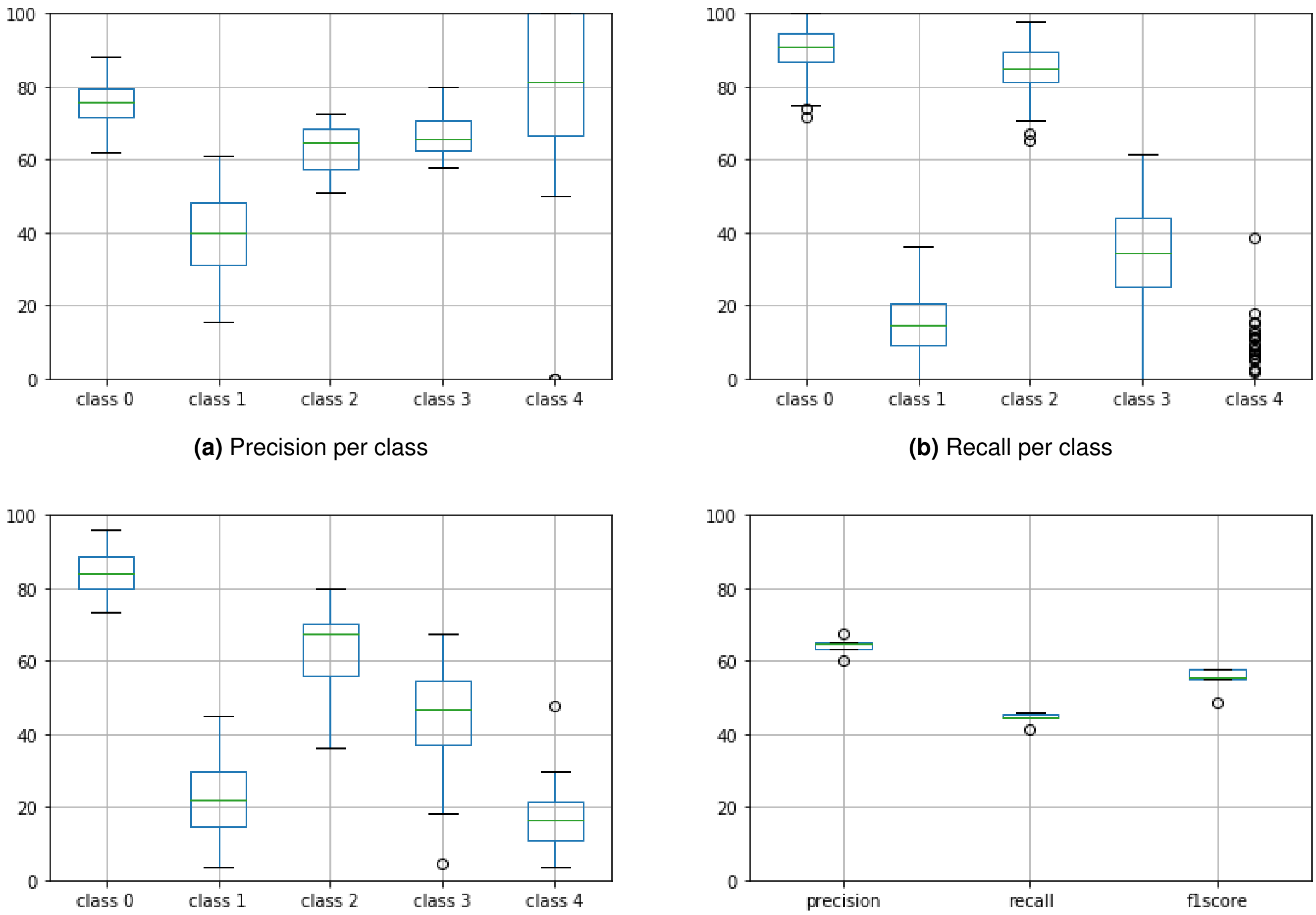
1earning rate lr	N hidden states	Training Loss	Evaluation metric
0.001	100		
0.01	100		
0.001	50		
0.01	50		

Table 3.13: LSTM neural network training for the 5-class problem for the VDLm2 link evaluation



(a) Precision per class

(b) Recall per class

(c) F1score per class

(d) Global performances

Figure 3.26: Performances of the LSTM neural network for the VDLm2 link for the 5-class problem

LSTM case scenario

We first tried on with the same amount of classes but with a slightly different distribution for the channel capacity class representation because the link properties is different from the VDLm2 one. The 5 classes are the following : class 0= 0-20%, class 1= 20-40%, class 2= 40-60%, class 3= 60-80%, class 4= 8-100% Then, we trained the network with the parameters shown in the Table 3.14, which gives us the performances presented in the Figure 3.27 on the validation set. The performances look very bad, with not a single global metric over 40% on average (Figure 3.27d). So we decided to handle another study with 4 classes represented as follows : class 0= 0-20%, class 1= 20-40%, class 2= 40-60%, class 3= 60-100%.

We tried this representation of classes to have a similar distribution among the classes in the training set. The training of the neural network is presented in the Table 3.15 with different sets of parameters. All the models achieve in the end a training loss lower than 1 for the training and validation set. We took the second one which presents a smoother training curve. The results on the whole validation set are presented in the Figure 3.28. Compared to the performances we had by taking five classes, we managed to increase the global scores: from 40% to 60% for the precision, 38% to 49% for the recall and 28% to 42% for the f1 score. However, the score per class is very scattered. The class 1 and 3 have a very low F1 score (Figure 3.28c), meaning that they are not well identified by the neural network.

In conclusion, the LSTM network we use is limited in identifying many classes with only a single feature (the RTT delay from the ICMP ping packet). For both the VDLm2 and LDACS scenarios, at least one of the classes always has a very low recall score, which hurts the global performances of the system.

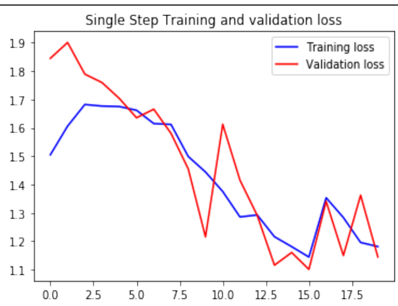
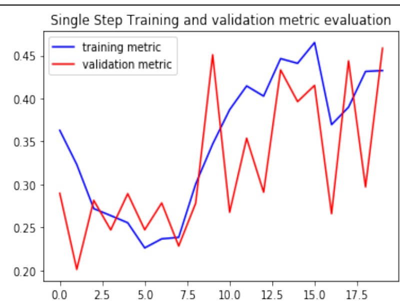
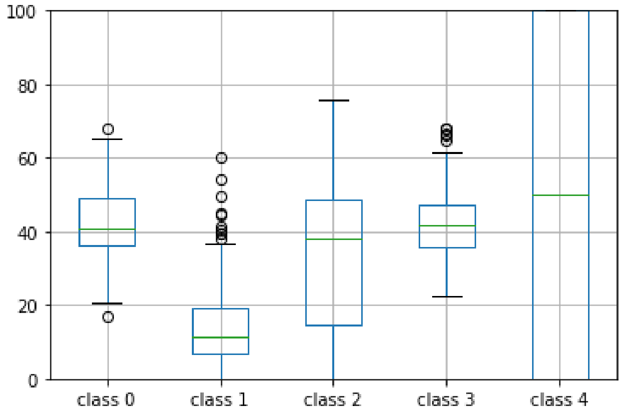
<table>
<tr><th>1earning rate lr</th><th>N hidden states</th><th>Training Loss</th><th>Evaluation metric</th></tr>
<tr><td>0.001</td><td>500</td><td>
</td><td>
</td></tr>
</table>

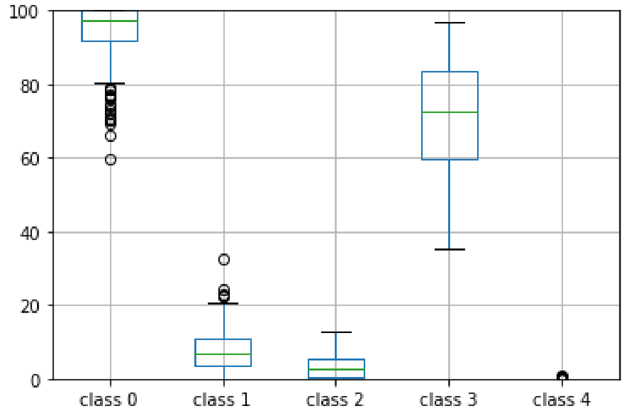
Table 3.14: LSTM neural network training for the 5-class problem for the LDACS link evaluation

4.4.3 LSTM for a regression problem

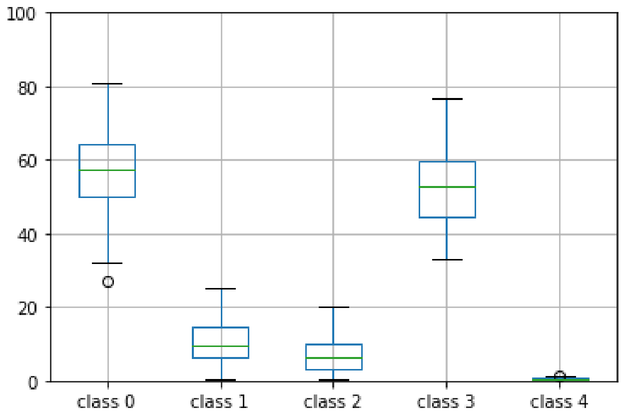
Another way to predict the link quality is to consider it as an real value between 0 and 1, leading us to a regression problem. To adapt our network to this new problem, we remove the Softmax layer that is used for multiclass problems



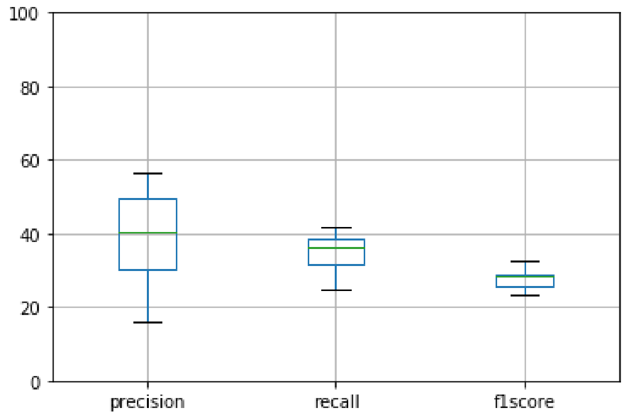
(a) Precision per class



(b) Recall per class



(c) F1score per class



(d) Global performances

Figure 3.27: Performances of the LSTM neural network for the LDACS link for the 5-class problem

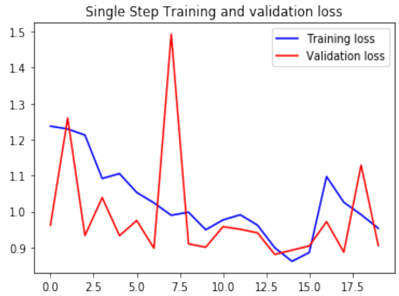
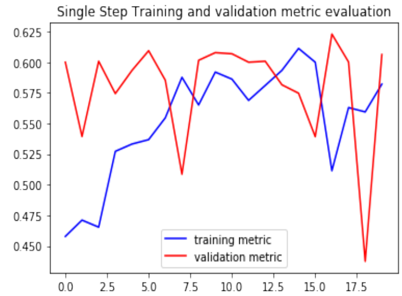
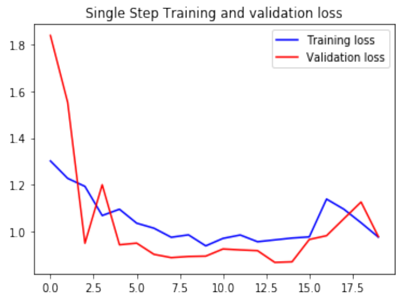
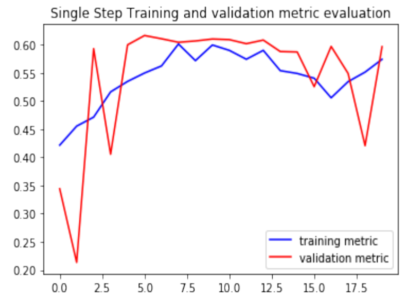
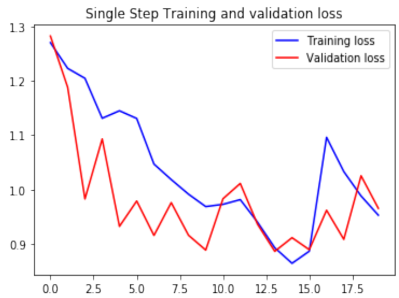
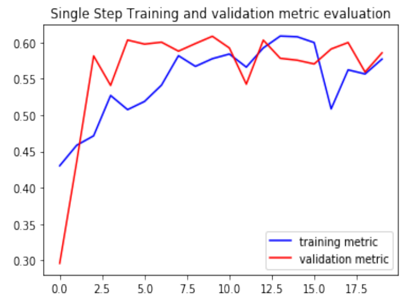
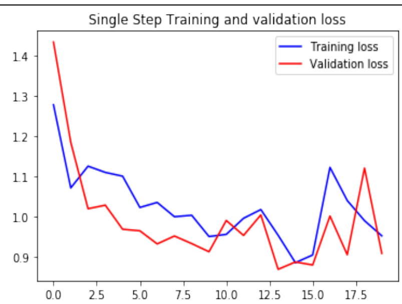
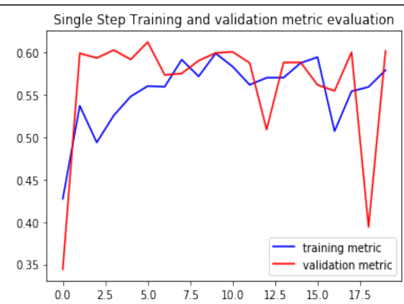
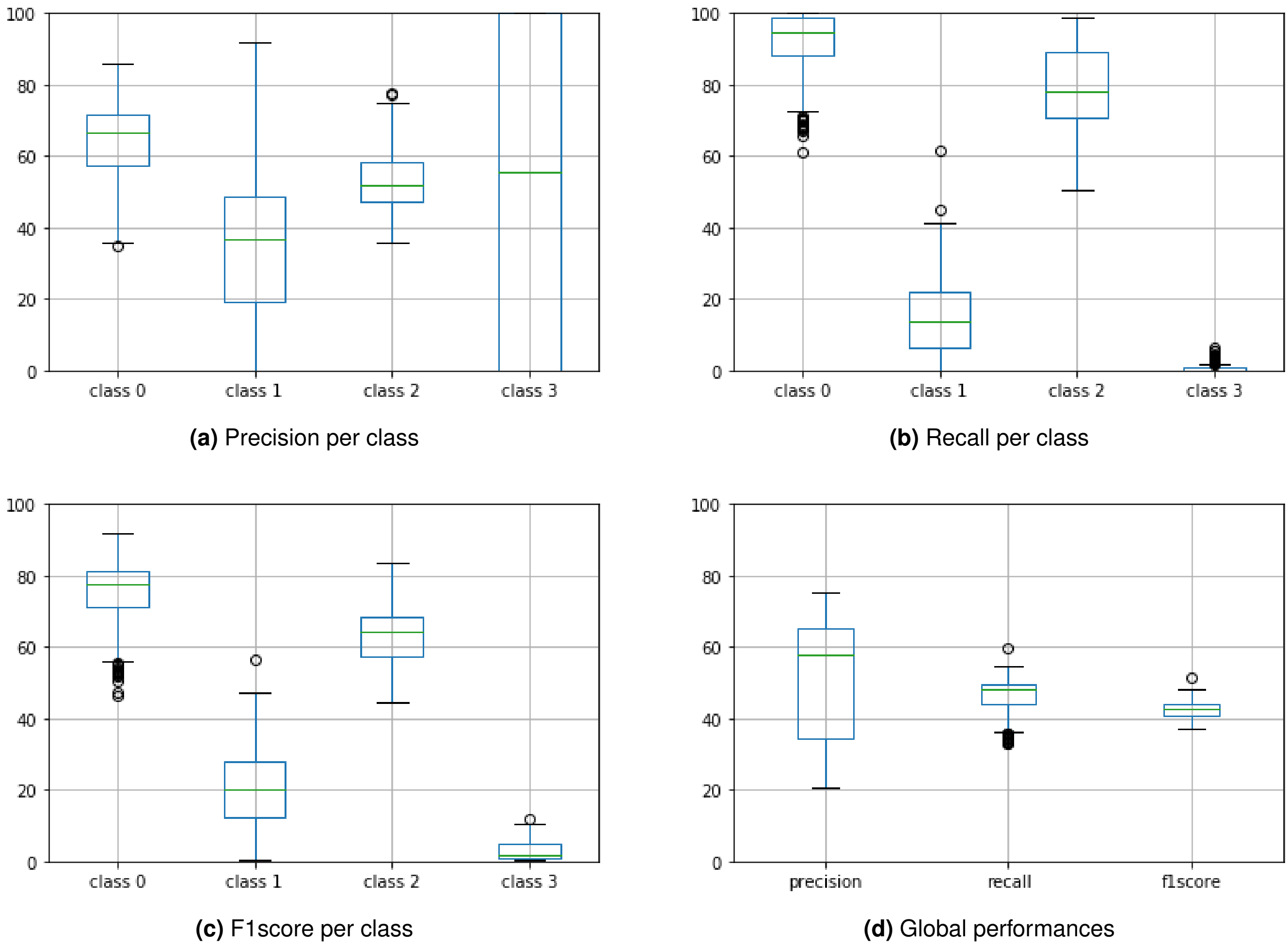
1earning rate lr	N hidden states	Training Loss	Evaluation metric
0.01	20		
0.01	100		
0.001	100		
0.01	200		

Table 3.15: LSTM neural network training for the 4-class problem for the LDACS link evaluation



(a) Precision per class

(b) Recall per class

(c) F1score per class

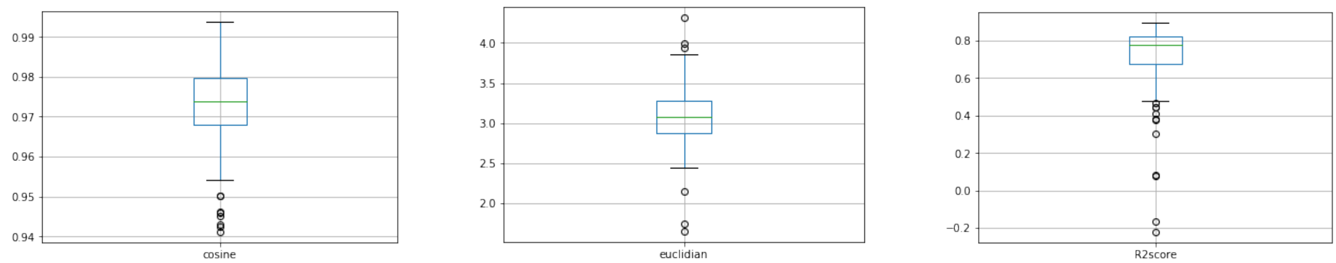
(d) Global performances

Figure 3.28: Performances of the LSTM neural network for the LDACS link for the 4-class problem

and replace it with a simple neural network layer (Dense(1) in the Keras framework) with a single output which is the predicted value of the link quality. We adapt the loss function and the evaluation metric function to fit the problem. For the evaluation metric, we choose the cosine metric, which helps to measure the similarity between 2 signals: The more it is close to 1, the more the signals are similar.

VDLm2 case scenario

We trained the neural network with different parameters. The results of the training is shown in the table 3.16. We can see that all the neural networks have roughly the same training loss and evaluation metric. So we chose the first one with the least hidden nodes for our prediction. To evaluate the entire validation set, we took the data corresponding to one aircraft during 24h, that represents 1440 values (one ping per minute), so the data in the Figure 3.29 represent the distribution of the aircraft prediction in the evaluation dataset. The cosine and the R2 score must be closer to 1 and the euclidean metric closer to 0 to have a good prediction. Overall the three scores show a good prediction by the neural network. An illustration of a prediction is given in the Figure 3.30. The model follows the variation of the channel state. However, at around the 400 th prediction, the model is not very accurate to detect the peak of 0.8.



(a) Cosine metric **(b)** Euclidean metric **(c)** R2 score

Figure 3.29: Performances of the LSTM neural network for the VDL link for the regression problem

LDACS case scenario

For the LDACS case scenario, the neural network training is represented in the table 3.17. The hidden states parameter does not seem to make a huge difference in the result between 100 and 200, so we choose 100 which runs faster. The performances on the validation set are pointed out in the Figure 3.31. The measures are realized per aircraft which have about 4320 samples (one probe every 20 seconds during 24 hours). In comparison with the VDL link prediction performances, there is not a big difference with the cosine score (0.962 instead of 0.975, Figure 3.31a), however the two other metrics demonstrate that the neural network is under-performing while predicting the LDACS link state. Indeed, the euclidean distance average value (Figure 3.31b) is 9, scaled by a factor of $\sqrt{3}$ because there are 3 times more data in the LDACS case, to compare with the VDL case, equals to 5.2, which is

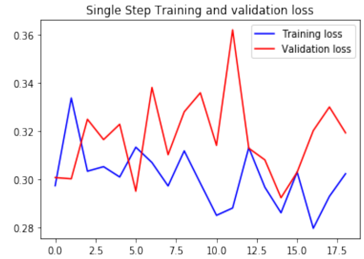
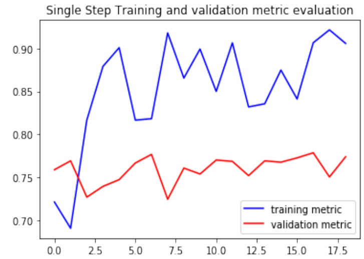
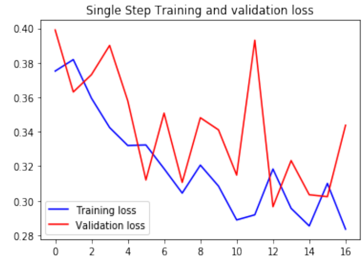
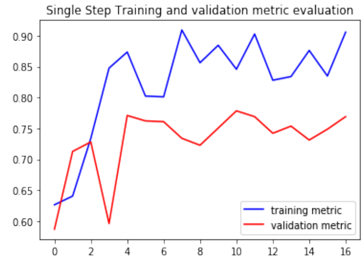
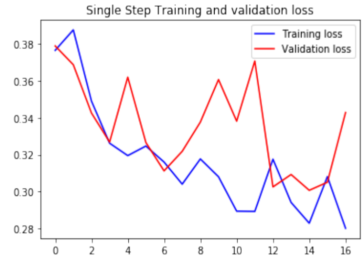
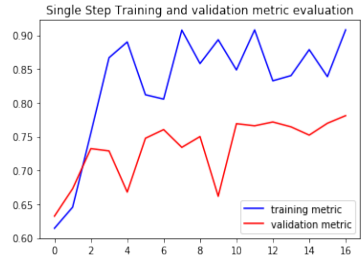
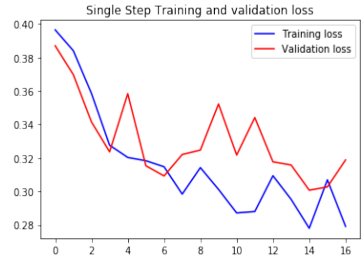
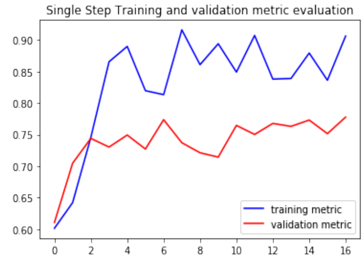
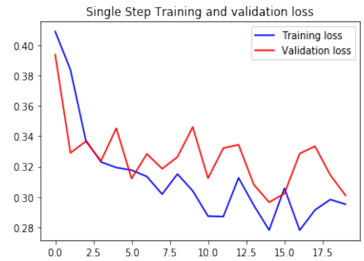
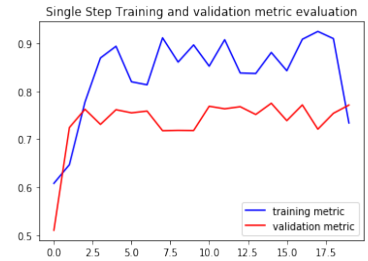
1earning rate lr	N hidden states	Training Loss	Evaluation metric
0.01	5		
0.01	10		
0.01	20		
0.01	50		
0.01	200		

Table 3.16: LSTM neural network training for the regression problem for the VDL link evaluation

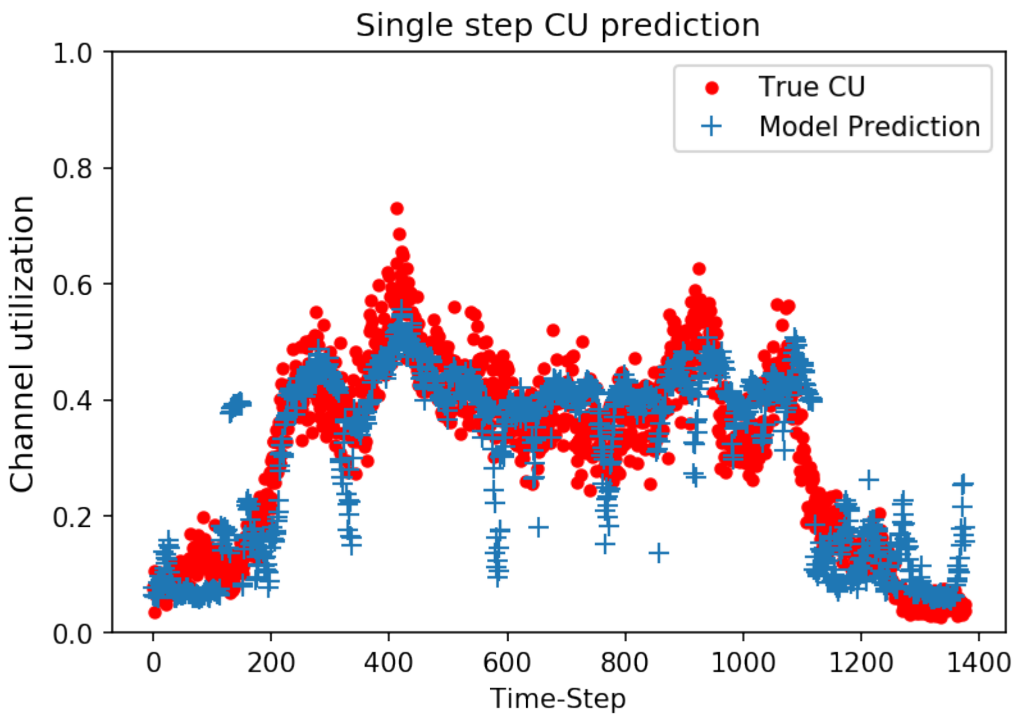
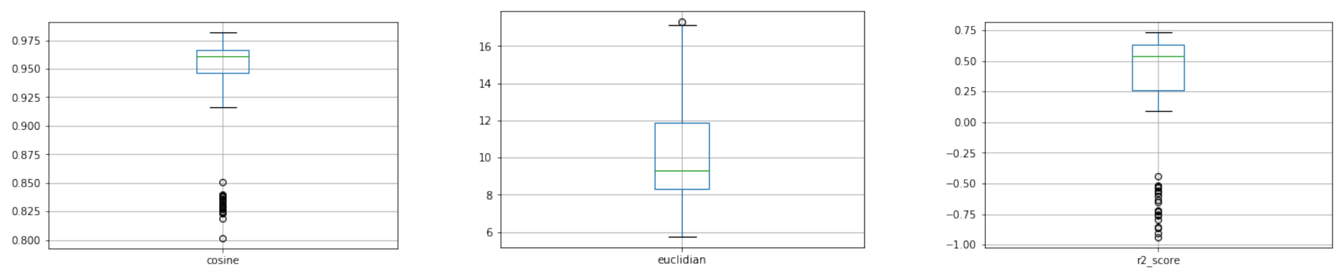


Figure 3.30: An example of the prediction for one aircraft during 24h for the VDL link

higher than 3.1. Beside, the r2 score for the LDACS case is very low with a value of 0.55, compared to the 0.8 in the case of VDL link. An example of a prediction over the LDACS link is given in the Figure 3.32. In addition to the highest values that are not well predicted, the low values of the channel states are also not well identified. But still, the variation of the channel state is correctly predicted.

In conclusion, solving the problem of predicting the channel state by using a LSTM neural network as a regression tool allows us to capture the variations of the channel state for both link technologies. However, the extreme values are still hard to predict. Taking more than one feature or enhance the training samples may help to better identify the different channel state values.



(a) Cosine metric **(b)** Euclidean metric **(c)** R2 score

Figure 3.31: Performances of the LSTM neural network for the LDACS link for the regression problem

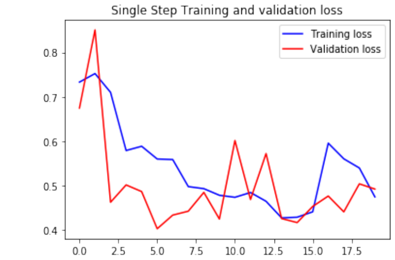
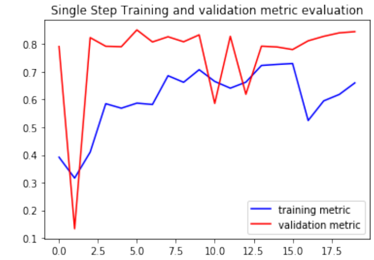
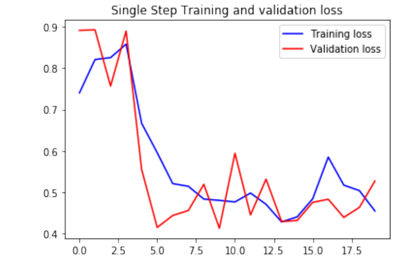
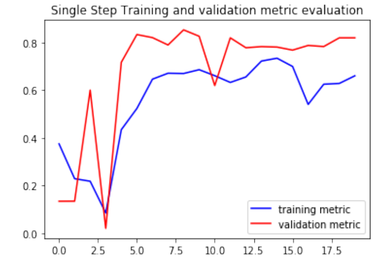
1earning rate lr	N hidden states	Training Loss	Evaluation metric
0.001	100		
0.001	200		

Table 3.17: LSTM neural network training for the regression problem for the LDACS link evaluation

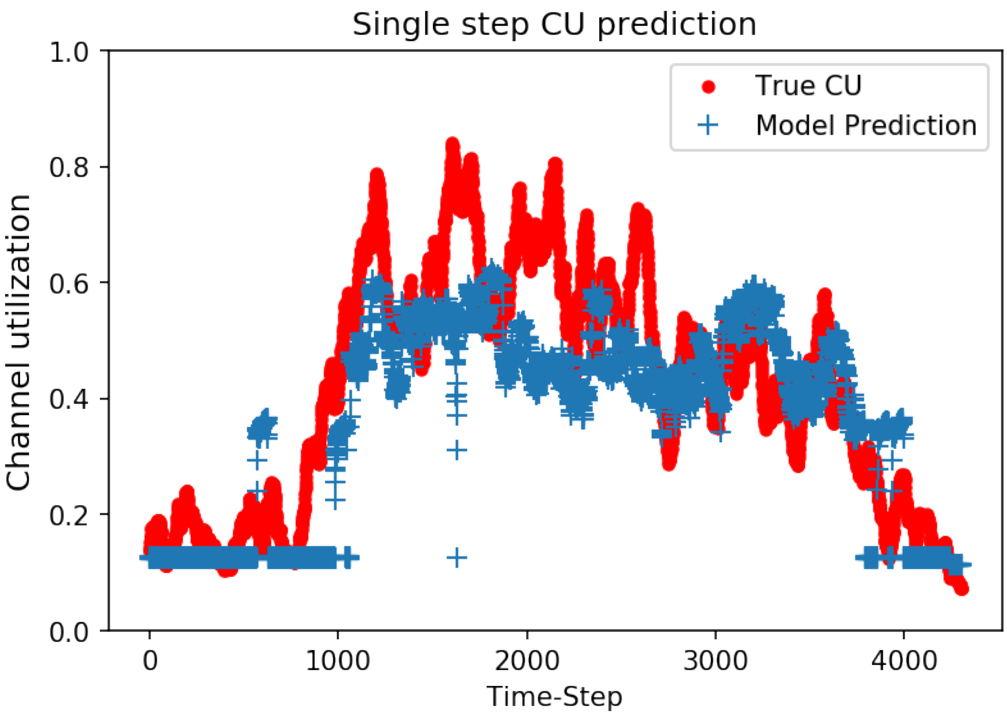


Figure 3.32: An example of the prediction for one aircraft during 24h for the LDACS link

4.4.4 Prediction over future states

Predicting the current link quality state is helpful, but in the case the quality is fluctuating a lot, this measure may not be sufficient to make a good decision, as this decision is only available for the current state. If the next link state is very different from the current one, another link decision must be performed at the next timestep and may trigger a link switching. Therefore, making a prediction of the link quality over multiple timesteps can help the system avoid this phenomenon. LSTM neural networks allow to capture a long term dependency and make a prediction over multiple timesteps. As the problem is more complicated, we add to our neural network another LSTM layer as shown in the Figure 3.33. We also modified the output layer which is just a neural network layer which outputs a prediction for each future timesteps. In addition, we are taking the regression approach, which based on the previous studies appears to present a better prediction than the multiclassification approach. Likewise, we used the same training loss score as well as the same evaluation metric score like the regression case.

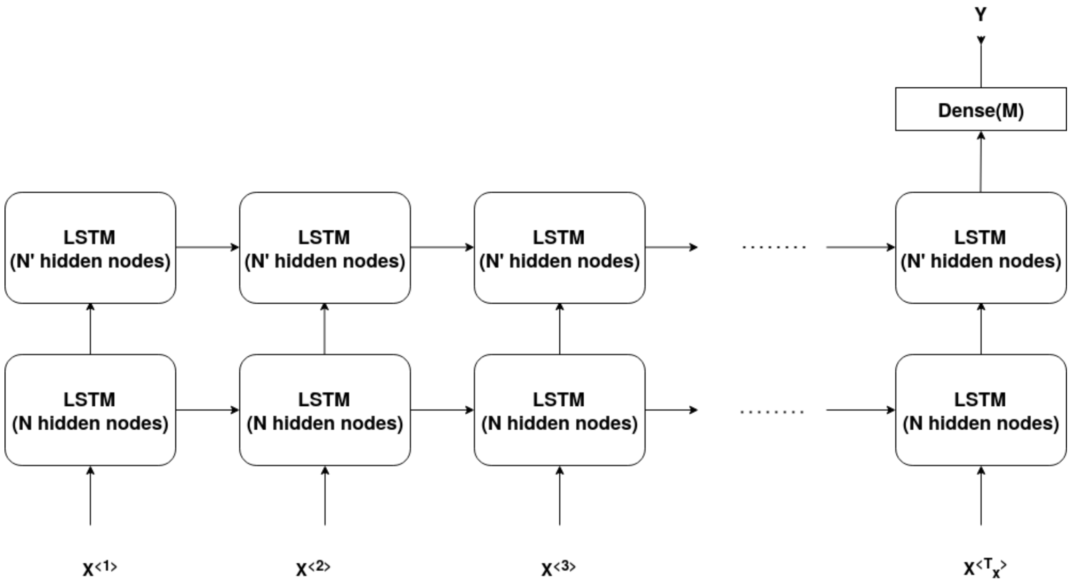


Figure 3.33: The LSTM neural network for link quality prediction over multiple timesteps

VDLm2 case scenario

The parameters of our neural network are shown in the Table 3.18, as well as the training curves. The training is performed with mini-batch of size = 32. The final results on the validation set are presented in the Figure 3.34. The X-axis of these figures represents the distance to the current time at which the neural network makes the prediction. We trained the neural network so that it can predict up to a distance of 10 timesteps, which corresponds in the case of the VDLm2 case scenario to 10 minutes. Compared to the single step prediction model, where the predictions results are presented in the Figure 3.29, there is not a significant gap in the average performances while looking at the three metrics. The cosine metric goes from 0.975 to 0.97, the euclidean metric is increased by 0.4 and the R2 score is reduced from 0.78 to 0.75 in average over all the prediction distances. Also, the results highlight that the neural network is accurate for all the distances up to 10, which is very satisfying.

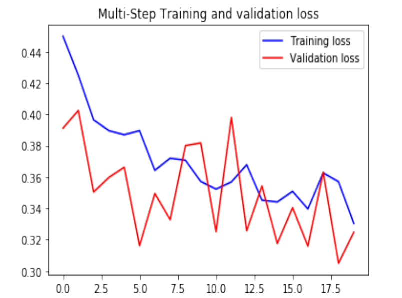
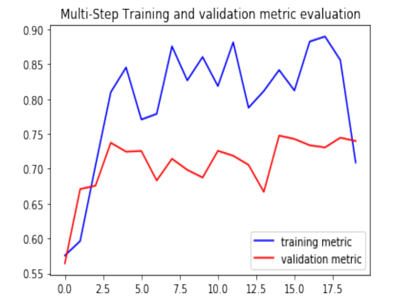
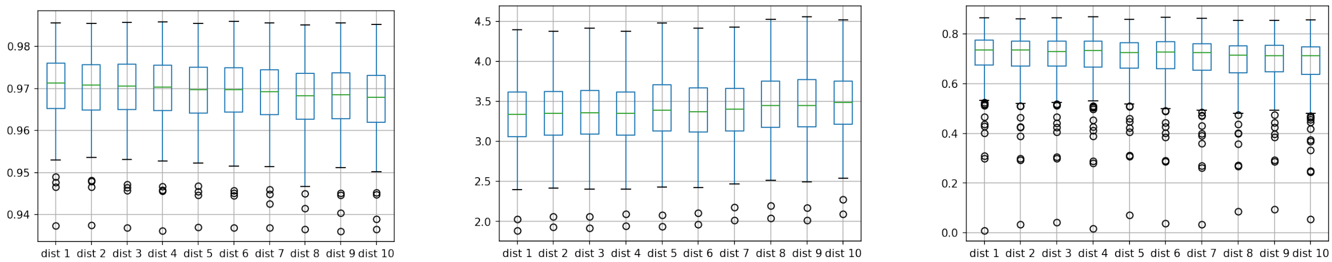
1earning rate lr	N hidden states	N' hidden states	Training Loss	Evaluation metric
0.01	50	4		

Table 3.18: Multi-step LSTM neural network training for the regression problem (over VDL link)



(a) Cosine metric **(b)** Euclidean metric **(c)** R2 score

Figure 3.34: Performances of the LSTM neural network for the VDL link for the multistep prediction problem

LDACS case scenario

The neural network parameters are summed up in the Table 3.19. We put more hidden states than in the VDLm2 case scenario because the size of the input data is higher. The performances on the evaluation set are represented in the Figure 3.35. We trained the algorithm so it can predict over 15 timesteps, which equals to a 5 minutes prediction (for the LDACS link, the aircraft sends a probe every 20 seconds). In comparison with the results we obtained previously for the single step prediction (Figure 3.31), all the metrics show a better performance for the multi-step predictions: the cosine metric is slightly higher (0.97 compared to 0.96), while the euclidean metric and the R2 score improve significantly, with respectively 6.8 instead of 9 and 0.75 instead of 0.5 ina verage. This result, while surprising, shows that it is quite complex to achieve good results with neural network with a short training (20 epochs in our case). Besides, as for the VDLm2 case scenario, the performances do not degrade that much with the distance, so the neural network can predict with the same amount of accuracy for a distance up to 15 for LDACS links.

In conclusion prediction of the link quality over future states is possible with a LSTM neural network. Besides, the future predictions reach the same level of performance in term of accuracy as the single step prediction for both

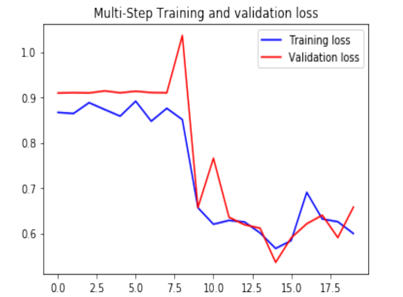
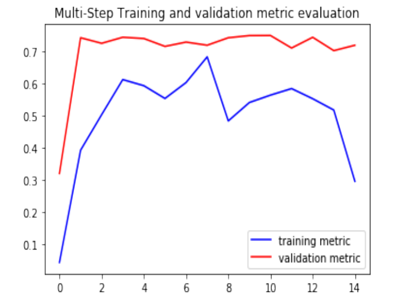
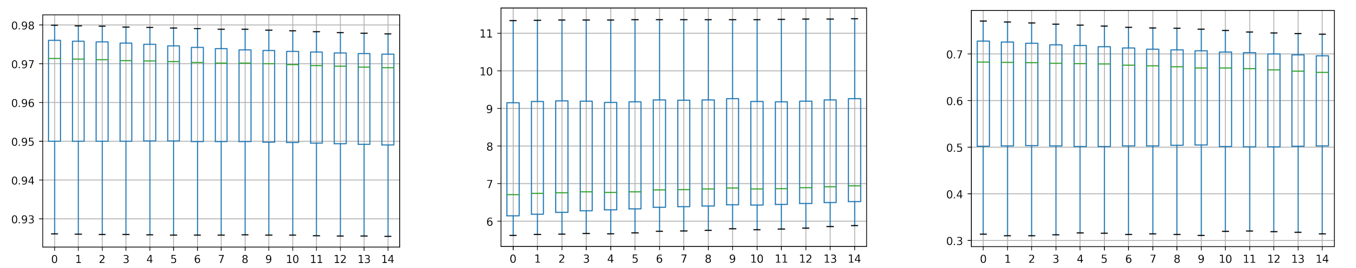
1earning rate lr	N hidden states	N' hidden states	Training Loss	Evaluation metric
0.01	60	10		

Table 3.19: Multi-step LSTM neural network training for the regression problem (over LDACS link)



(a) Cosine metric **(b)** Euclidean metric **(c)** R2 score

Figure 3.35: Performances of the LSTM neural network for the LDACS link for the multistep prediction problem

technology links. Therefore, it may be a useful indicator in order to make the decision at the second step of the multilink algorithm.

4.5 Prediction methods summary

In this section, we have assessed the performances of different prediction methods to estimate the quality of the secondary communication links towards which the multilink decision algorithm may decide to offload some traffic. Our conclusion is that the HMM method is not suited for our case scenario, however a HMM of higher order may be able to achieve a good prediction. For the two others methods, if we just want to perform a single step prediction, the threshold based algorithm seems to be the best choice as the LSTM neural network doesn't perform significantly better for the computational it requires. However, when making the decision to switch to another communication link, it is important to have a knowledge of the future states of the link in order to limit the number of handovers. The LSTM used as a regressor, has shown good performances while predicting the future state of the link. The accuracy is indeed as high as the single step prediction model. To see the benefits of having knowledge of the futures link states, further work including the definition of a multilink decision algorithm that used our link quality estimation method will be performed.

Besides, with our laptop (Intel Core i77-8550U, 1.80GHz, 4 cores), the LSTM algorithm developed needs in average 0.33ms (taken from 1000 values) to compute the quality of the link. While this value is relatively low, compared to the delay requirements for critical aeronautical applications 2.7, the computation onboard is not comparable with our laptop, and the delay required to perform such computation is expected to be higher. However, the link quality evaluation is performed periodically at each ICMP packet received, so the information on the link quality may be already available when the multilink algorithm needs it.

Conclusions

In this chapter, we proposed a method to predict the quality of the different radio links in the context of the ATN/IPS. A passive method based on the data traffic and the signalling traffic at the upper layers only helps in determining the quality of the primary link and cannot be applied for secondary links. Therefore, we proposed a prediction method based on active probing at the application layers in order to measure secondary links quality, that will help the multilink decision algorithm to offload or handover towards the selected link. We have seen that the ping application providing the RTT delays measures does not exceed 10% of the used capacity for LDACS and VDLm2 links even when the cell is highly congested (when the number of aircraft reaches the PIAC value).

This active method is based on the ICMP ping packets with a short TTL to retrieve the RTT corresponding to the technology link. Based on the IP source address which sends the ICMP ERROR packet, we can deduce which link has been probed. Then, we conducted a study on different methods to analyse the RTT values and deduce the link quality in terms of its level of congestion. We first assessed the link quality with a classification approach. The probabilistic model with the HMM doesn't accurately predict the state of the link. However, a more complex model with a higher order HMM may succeed in predicting the state of the link as it takes up to N (N being the order of the HMM) previous states to predict the future channel state. Indeed we have shown that the link state dependency is highly correlated with previous states for both the LDACS and VDLm2 links. The simplest method, based on threshold detection, had a highest global precision rate with almost 80% for detecting among three classes of link. Taking into account the limited computational resources on the airborne router, such algorithm can be easily implemented onboard to make the decision on the link to switch or to offload the traffic. However, it only allows the prediction of the current state of the link and does not foresee the future state of the link.

In order to predict the future variation of the links, algorithms based on the LSTM neural network are suitable for this task. For this matter, we assessed the link quality by taking a regression approach. We demonstrated that for both LDACS and VDLm2 links, the neural network presents the same results in terms of accuracy for a prediction distance up to 10min and 5min for the VDL and LDACS links respectively. These results are based on three different metrics often used for measuring the distance between two series.

To further extend our results, it may be interesting to study the accuracy of these statistical tools on other set of air traffic data by considering other dense regions such as Paris or London or regions with low traffic density. Also, these data can be used to further train the neural network to increase its accuracy for all kind of air traffic data.

Finally, an approach with an unsupervised learning method, as proposed in [SSBG+20] where a Convolutional Neural Network (CNN) is combined to a LSTM network to perform medical classification tasks, can be investigated here to help in the determination of the different link quality classes. Also a new neural network architecture TCN (Temporal Convolutional Network) has recently demonstrated similar performances compared to the LSTM network in the weather forecast prediction that also includes time series data [YMW+20], therefore it will be interesting to see the benefits of this approach in our context.

Conclusions and further work

This thesis on the new aeronautical network ATN/IPS takes place in the context of the improvement of aeronautical communications and particularly air-ground communications. Indeed, the current wireless link technologies and the current network infrastructure cannot meet the requirements of new safety and airline operational applications that request more and more capacity. Besides, these new requirements must be put in the context of an expected continuous growth of the air traffic.

Thereby, a lot of recent work has focused on studying new communication systems for the civil aviation, notably in the European project SESAR and its American counterpart NextGen. These projects aims at proposing and specifying innovative systems in the domain of the communication, navigation and surveillance, in order to meet the global need of the Air Traffic Control for the next decades.

For the communication domain, new solutions based on cellular systems for direct communication with a ground base station in continental areas, and satellite system for oceanic and remote areas are expected to be deployed in the future decade. In such a heterogeneous environment, new challenges and opportunities arise. In this thesis, we tackle the problem of both the aircraft network mobility and the multilink. Indeed, during the aircraft transfers from one access point to another, the ongoing communication may be disrupted if this event is too long. Therefore, the definition of a specific mobility protocol for this matter need to be defined. The second problem aims at optimizing the use of the overall available radio resources in order to increase the quality of services. As described above, the presence of the multiples links has to benefit the aircraft by providing them the best possible connection. Whenever the aircraft establishes several connections to the ATN/IPS through these different links, an adequate multilink algorithm needs to choose which link(s) offer(s) the best services. The solutions proposed in this work also takes into consideration the specific requirements of the aeronautical environment.

Aeronautical IP mobility protocol

In the first part of the thesis, after introducing the context of the ATN and its evolution, we propose a mobility protocol capable of managing all the aircraft mobility scenarios. Originally, the Internet has not been developed to handle mobiles nodes, but with the recent growth of mobile nodes and their need to remain connected to Internet, the need of a network mobility protocol has gained a lot of attention. We first realized a state of the art on the protocols able to manage the network mobility in IP networks, and weight the pros and cons of each of these protocols. These protocols range from the network to the application layer, but we are only interested in those at the network layer in order to facilitate the integration with the aeronautical applications. As none of the already existing protocols satisfy all the aeronautical requirements, particularly in terms of signalisation traffic on the air/ground link, low cost implementation onboard the aircraft and global network mobility, we came up with our own solution: P-LISP.

Our solution is a combination of the PMIPv6 to handle the intra-domain mobility and the LISP for the inter-network mobility. We take advantage of both the network-based solutions to avoid a high level of complexity onboard, meaning that the ground routers in the core and edge of the ATN/IPS handle the aircraft mobility. The principle is as follows: the aircraft gets a fixed home prefix based on its identifier from the subnetwork's local agent it is attached to, which allows him to connect to the ATN/IPS. Then the local agent informs the mapping system, in the core of the ATN/IPS, of the association between its IP address and the aircraft's identifier, meaning that the aircraft is currently reachable by this local agent's subnetwork. In case of an intra-domain handover, the signalling is limited to the subnetwork in which the local agent updates the location of the aircraft, from the previous access router to the next access router. While for inter-domain handovers, the association in the mapping system is updated by the new aircraft's local agent and the mapping system broadcasts this information to routers that have previously sent packets toward the aircraft. In this way, we keep the signalling exchange with the aircraft as minimum as possible to handle its network mobility.

Performances assessment of the solution

We then assess the performances of our mobility solution by comparing it with a standard mobility protocol MIPv6 combined with PMIPv6. The assessment is realized with the help of the OMNeT++ software. Firstly, we developed a framework based on the INET one that already provides all the basic network protocols. However, the INET framework only proposes the IEEE wireless technologies. So at first, we need to develop our own generic wireless network interface controller to simulate an aeronautical radio link. We used a ideal radio propagation model combined with the CSMA protocol to simulate the wireless link access layer. In addition, we developed a handover manager inside this interface in order to avoid the ping pong effect that happens when the aircraft is covered by two ground stations. The handover policy is for now based on a subnetwork priority level, such as in the Airbus ACR product, meaning that as soon as the aircraft detects a new ground station that has a higher priority in the list, it will drop the previous link to establish a new one with the ground station having the highest priority.

We designed two scenarios to evaluate our proposal. In the first one, we implemented our P-LISP solution inside the network nodes: the mobile node (herein an aircraft) remains unchanged and only has a normal IPv6 stack, whereas the ground routers are enhanced with our mobility protocol. In the second scenario, we implemented the standard mobility solution in which both the mobile nodes and and the ground routers are modified to integrate the MIPv6 and PMIPv6. The simulation lasts for 1200s and the aircraft is making one inter-domain handover followed by one intra-domain handover during that time period. We assess the performances in terms of the handover delay and the packet end-to-end delay. For intra-domain handovers, both solutions achieve the same results for the handover delay, but for inter-domain handovers, our solution helps to reduce the handover delay by a factor of two, going from an average of 6s with the MIPv6 solution to 3s with the P-LISP. This is explained by the fact that with the MIPv6, the aircraft needs to configure a new IP address after the handover is completed, which takes around two seconds to perform the stateless IP address auto-configuration. In addition, another binding association is performed between the aircraft and its Home agent with the MIPv6, that is subject to a round-trip delay between the two entities. In terms of the packet end-to-end delay, our solution performs slightly better in the different considered scenarios. Indeed, it has the advantage of being independent from the location of a Home agent because it relies on a mapping system that updates the location of the aircraft for the ground routers.

Method to estimate the link quality

In the second part of the thesis, we are interested on the opportunity of the multilink perspective in the ATN/IPS. In the aeronautical heterogeneous environment composed of many air/ground communication links, the aircraft may at some points be covered by multiple links. In this context, the capacity of being able to offload the traffic from one link to another is a required feature in the new network infrastructure. Indeed, in the previous ATN, packets may suffer from a huge delay as the onboard routing policy is based on a subnetwork priority. As the router only gets the information of the link status, the transfer from one link to another in the case of a congestion is only performed after the primary link is dropped down. In order to provide such a feature, the multilink algorithm must first be able to gather information from the available links. In the literature, the quality of the link is often reflected with the radio or link parameters such as the SNR or the bandwidth and is assumed to be provided by the radio itself. The IEEE community has developed the MIH standard to homogenize the information from the different IEEE link technologies.

In this work, we propose a method to get rid off the information coming from the aeronautical link access layer as it is technology-dependent and also needs to be homogenized. Indeed, in order to facilitate the deployment of our solution, we cannot count on lower layer information as it will require to update all the existing communication systems and develop a MIH equivalent for the aviation. Our method is based on probe packets to estimate the quality of the link in terms of the used capacity. We make sure to probe only the air/ground link by setting up the TTL field to a small value, that will trigger a Time Exceeded message in response by the air/ground access router. In this way, we make sure that the RTT delay is only due to the air/ground link delay. This delay directly gives an indication of the used capacity by the link. We then compare three types of analytical tools to estimate the used capacity based on the history of the RTT delays. The first method is based on thresholds, the second one is a probabilistic approach using hidden Markov models, and the third one relies on a machine learning technique for time series data (LSTM).

Evaluation of different analytical tools

In collaboration with the University of Pisa, we implement our estimation method on the SAPIENT framework, which has been developed for a SESAR H2020 project. Our objective is to determine which one of the three solutions performs better. We perform the evaluation on two different terrestrial link technologies, namely VDLm2 and LDACS, which integrates two different MAC policies. The first one is based on the CSMA p-persistent protocol, an extended version of the CSMA protocol, while the second one relies on the TDMA protocol. The choice of the MAC protocol may impact our solution as it directly affects the link delay. The case scenario is based on realistic air traffic data: we performed an air traffic trajectory replay above a cellular ground station in Maastricht during a day. Our evaluation set is based on the month of February 2020. The channel capacity varies according to the number of aircraft that send UDP data traffic toward a ground end-system. The history of RTT provided as inputs of these algorithms corresponds to 20min of simulation time.

We first conducted an estimation based on a link quality classification where the link state is either Good, Medium or Bad to indicate its level of used capacity. This is a first improvement to the current link state information inside the onboard router that only knows whether the link is up or down. We demonstrated that a simple hidden Markov model doesn't perform well for the two link technologies, as the successive probe delay data are too correlated. The threshold-based method provides a good estimator with a precision rate of almost 80% for the LDACS and VDLm2 technologies. However, the threshold-based algorithm is different for the two link technologies. Indeed, the LDACS delay is more deterministic, therefore metrics based on the average delay or the delay distribution perform well in this situation. We also created a metric called the 1NZQTH for the LDACS link which measures the distribution of the past delays. We showed that this metric combined with the average RTT is a good estimator for the link quality. However, for the VDLm2 link technology, as the delay is more random, such metrics are less efficient than those considering the standard deviation. In comparison, the machine learning model is as accurate as the threshold-based method but with a higher computational cost (up to thousands of trainable parameters). To go further, we then studied how we can predict the link quality over multiple future steps. For this regard, we use the machine learning model and train it to predict the next values of the channel's used capacity (in percentage). We demonstrate that, based on three different metrics, the LSTM neural network is able to predict with a same level of accuracy for a period of 5 to 10 min for an input time series data of 20min. It means that the LSTM is good at predicting the trend of the used capacity, even if there is still a bias that goes up to 20% for both the LDACS and VDLm2 links, particularly when it tries to predict a high level of the used capacity. This bias can be mitigated by collecting more data in our training set.

Further work

The work carried out during this thesis have proposed network solutions for the deployment of the ATN/IPS, foreseen for the next decade. Following this research work, future studies can be considered in the domain of the network mobility and multilink: the specification of a virtual interface on the router onboard, other types of sharing prefix mechanisms, and a link decision algorithm based on our information gathering method. Also the SAPIENT framework can be enhanced to allow more mobility protocols and more link technologies.

We have shown that our P-LISP protocol is able to manage the different handover scenarios. However, we have not discussed the case when the onboard router is equipped with multiple wireless NICs. Indeed, in the IP domain, each of these interfaces will retrieve a prefix from the subnetwork they are attached to, and even if they get the same prefix based on the aircraft identifier, they will configure a different IPv6 address based on the stateless address auto-configuration in IPv6. However, one of the requirements is that the aircraft must be reachable with a unique IPv6 address. One way to solve this problem is to consider a virtual network interface on top of the wireless NICs. This virtual interface must configure a global unique IPv6 address that will be used for its connection to the ATN/IPS. The mechanisms that will allow such this feature must be addressed in order to be compatible with our P-LISP solution.

In addition to the network mobility problem, to further enhance our solution, the "broadcasting mechanism" that allows the local agents to share the home prefix information can be improved and further studied. Indeed, we assume that the home prefix information is available in all the local agents' database. This assumption relies on the cooperation of all the subnetwork providers. But in the case they do not want to cooperate, the local agents must find a way to retrieve the aircraft's home prefix in a small amount of time in order to enable a seamless handover.

For the multilink perspective, firstly, we have only taken data from the Maastricht region. Another study on different regions with different air traffic density may be conducted to make sure that our estimation technique is replicable with the same parameters setup. Secondly, decision algorithms can be found in the literature. They only focus on solving the Multiple Attributes Decision-Making MADM) problem: [Rib96][Zha04][WL13] proposes a fuzzy approach, [KMBWW09][Yav15] a analytical hierarchical process (AHP) and [KK17] a game theory approach. However, the integration in the aeronautical domain remains a subject of study. Particularly, it might be interesting to compare these approaches with a decision algorithm based on the predictions made by the machine learning method we defined. Also, to further improve the multilink algorithm, we can consider adding the passive method to assess the primary link state in order to reduce the probing on secondary links all the time, and thus to alleviate the amount of signalling. Indeed, there is no need to probe the secondary links and run the multilink decision algorithm when no congestion is detected on the primary link. Another line of research might study the comparison of a decentralized approach where all the aircraft decide by themselves which link to use, to a more centralized approach where a ground coordinator distributes the available resources to mitigate the congestion on certain links and maximise the global resources use.

To assess the performances of these solutions, the SAPIENT framework and OMNeT++ can provide a good tool to test out several scenarios. For instance, integrating it into this framework can help to further demonstrate the efficiency of our mobility solution. Also, the integration of new link technologies such as the AeroMACS, can provide further interesting results for the study of network mobility protocols or multilink scenarios. [HL16]

Publications

International conferences

- Alexandre Tran, Alain Pirovano, Nicolas Larrieu, Alain Brossard, and Stephane Pelleschi. IP Mobility in Aeronautical Communications. In Nets4, 13th International Workshop on Communication Technologies for Vehicles, Nets4Aircraft and UAV session, volume Lecture Notes in Computer Science of Communication Technologies for Vehicles - 13th International Workshop, Nets4Cars/Nets4Trains/Nets4Aircraft 2018, pages pp 16–26/ISBN 978–3–319–90370–5,Madrid, Spain, May 2018. Springer
- T. N. Alexandre, P. Alain, and L. Nicolas. Managing aircraft mobility in a context of the ATN/IPS network. In 2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC), pages 1–9,2019

Journal paper

- Alexandre Tran, Alain Pirovano, Air-ground link quality prediction in the ATN/IPS network. Submitted in Journal of Aerospace Information Systems (waiting for review)

Bibliography

[3GP10] 3GPP. "3gpp ts 23.402". https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?s 2010.

[AAN19] T. N. Alexandre, P. Alain, and L. Nicolas. Managing aircraft mobility in a context of the atn/ips network. In *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*, pages 1–9, 2019.

[ABB18] Emilio Ancillotti, Simone Bolettieri, and Raffaele Bruno. RTT-Based Congestion Control for the Internet of Things. In Kaushik Roy Chowdhury, Marco Di Felice, Ibrahim Matta, and Bo Sheng, editors, *International Conference on Wired/Wireless Internet Communication (WWIC)*, volume LNCS-10866 of *Wired/Wireless Internet Communications*, pages 3–15, Boston, MA, United States, June 2018. Springer International Publishing. Part 1: IoT and Sensor Networks.

[AEE20] AEEC. Internet protocol suite (ips) for aeronautical safety services, 2020.

[ANS] Ansa.

[AT07] Ihsan A Akbar and William H Tranter. Dynamic spectrum allocation in cognitive radio using hidden markov models: Poisson distributed case. In *Proceedings 2007 IEEE SoutheastCon*, pages 196–201. IEEE, 2007.

[BA08] C. Bauer and S. Ayaz. A thorough investigation of mobile ipv6 for the aeronautical environment. In *2008 IEEE 68th Vehicular Technology Conference*, pages 1–5, Sep. 2008.

[BBJ92] David A. Borman, Robert T. Braden, and Van Jacobson. TCP Extensions for High Performance. RFC 1323, May 1992.

[BCM12] C. Bernardos, M. Calderón, and T. Melia. Pmipv 6 : A network-based localized mobility management solution. 2012.

[Ber16] Carlos J. Bernardos. Proxy Mobile IPv6 Extensions to Support Flow Mobility. RFC 7864, May 2016.

[BFA07] R. Baldessari, A. Festag, and J. Abeille. Nemo meets vanet: A deployability analysis of network mobility in vehicular communication. In *2007 7th International Conference on ITS Telecommunications*, pages 1–6, 2007.

[BFM13] G. Bartoli, R. Fantacci, and D. Marabissi. Aeromacs: A new perspective for mobile airport communications and services. *IEEE Wireless Communications*, 20(6):44–50, 2013.

[CAS] Castalia.

[CCL11] T. Chen, J. Chen, and Z. Liu. Secure network mobility (senemo) for real-time applications. *IEEE Transactions on Mobile Computing*, 10(8):1113–1130, 2011.

[CLP+08] Kuntal Chowdhury, Kent Leung, Basavaraj Patil, Vijay Devarapalli, and Sri Gundavelli. Proxy Mobile IPv6. RFC 5213, August 2008.

[CN17] D. Cazau and G. Nuel. Investigation on the use of hidden-markov models in automatic transcription of music, 2017.

[CQ10] Z. Chen and R. C. Qiu. Prediction of channel state for cognitive radio using higher-order hidden markov model. In *Proceedings of the IEEE SoutheastCon 2010 (SoutheastCon)*, pages 276–282, 2010.

[CRRI11] B. R. Chandavarkar, G. Ram, M. Reddy, and M. India. Improvement in packet drop during handover between wifi and wimax. 2011.

[CSB+17] G. Capizzi, G. L. Sciuto, F. Beritelli, F. Scaglione, D. Połap, K. Ksiażek, and M. Woźniak. Available bandwidth estimation in smart vpn bonding technique based on a narx neural network. In *2017 Federated Conference on Computer Science and Information Systems (FedCSIS)*, pages 601–606, 2017.

[CSBM05] Claude Castelluccia, Hesham Soliman, Ludovic Bellier, and Karim El Malki. Hierarchical Mobile IPv6 Mobility Management (HMIPv6). RFC 4140, August 2005.

[CVS18] Chiara Caiazza, Antonio Virdis, and Giovanni Stea. Simulating lisp-based multilink communications in aeronautical networks. In Anna F\"orster, Asanga Udugama, Antonio Virdis, and Giovanni Nardini, editors, *Proceedings of the 5th International OMNeT++ Community Summit*, volume 56 of *EPiC Series in Computing*, pages 43–51. EasyChair, 2018.

[CXYX19] Juan Chen, Huanlai Xing, Hai Yang, and Lexi Xu. *Network Traffic Prediction Based on LSTM Networks with Genetic Algorithm*, pages 411–419. 04 2019.

[CYZ13] Hong Cheng, Jihang Ye, and Zhe Zhu. What's your next move: User activity prediction in location-based social networks. In *Proceedings of the 13th SIAM International Conference on Data Mining, May 2-4, 2013. Austin, Texas, USA*, pages 171–179. SIAM, 2013.

[dFdSdSRdJP09] L. F. C. C. d. Figueiredo, H. M. C. d. Silva, C. M. d. S. Rabadao, and A. M. d. J. Pereira. Wireless networks interoperability - wifi wimax handover. In *2009 Fourth International Conference on Systems and Networks Communications*, pages 100–104, 2009.

[dlOBS+08] Antonio de la Oliva, Albert Banchs, Ignacio Soto, Telemaco Melia, and Albert Vidal. An overview of ieee 802.21: Media-independent handover services. *Wireless Communications, IEEE*, 15:96 – 103, 09 2008.

[dlOMV+07] Antonio de la Oliva, Telemaco Melia, Albert Vidal, Carlos J Bernardos, Ignacio Soto, and Albert Banchs. Ieee 802.21 enabled mobile terminals for optimized wlan/3g handovers: a case study. *ACM SIGMOBILE Mobile Computing and Communications Review*, 11(2):29–40, 2007.

[Dul06] Andrew Dul. Global ip network mobility using border gateway protocol (bgp). 04 2006.

[EBO+02] Thierry Ernst, Ludovic Bellier, Alexis Olivereau, Claude Castelluccia, and Hong Lach. Mobile Networks Support in Mobile IPv6 (Prefix Scope Binding Updates). Internet-Draft draft-ernst-mobileip-v6-network-03, Internet Engineering Task Force, March 2002. Work in Progress.

[EL08] Lars Eggert and Julien Laganier. Host Identity Protocol (HIP) Rendezvous Extension. RFC 5204, April 2008.

[EtFAAF06] EUROCONTROL and the Federal Aviation Administration (FAA). Communications operating concept and requirements for the future radio system - version 2.0. 2006.

[EUR] EUROCONTROL. Demand data repository. `https://www.eurocontrol.int/ddr`.

[Fel10] ALECU Felician. The wimax technology. *Oeconomics of Knowledge*, 2, 04 2010.

[FFML13] Dino Farinacci, Vince Fuller, David Meyer, and Darrel Lewis. The Locator/ID Separation Protocol (LISP). RFC 6830, January 2013.

[FJL09] J. Fu, H. Ji, and X. Li. User-adaptive vertical handover scheme based on mih for heterogeneous wireless networks. In *2009 5th International Conference on Wireless Communications, Networking and Mobile Computing*, pages 1–4, 2009.

[GK16] M. Gohar and Seok-Joo Koh. Inter-domain mobility management based on the proxy mobile ip in mobile networks. *Journal of Information Processing Systems*, 12:196–213, 06 2016.

[HD98] Bob Hinden and Dr. Steve E. Deering. Internet Protocol, Version 6 (IPv6) Specification. RFC 2460, December 1998.

[HL16] Bernhard Haindl and Manfred Lindner. Ground based lisp for multilink operation in atn/ips communication infrastructure. pages 1–10, 09 2016.

[HS97] Sepp Hochreiter and Jürgen Schmidhuber. Long short-term memory. *Neural computation*, 9(8):1735–1780, 1997.

[HVA17] Thomas R. Henderson, Christian Vogt, and Jari Arkko. Host Multihoming with the Host Identity Protocol. RFC 8047, February 2017.

[IGM07] E. Demaria I. Guardini and M. La Monaca. Mobile ipv6 deployment opportunities in next generation 3gpp networks. 16thIST Mobile and Wireless Cmmunications Summit, 2007.

[INE] Inet framework.

[KGdSM14] B. Y. L. Kimura, H. C. Guardia, and E. d. S. Moreira. A session-based mobile socket layer for disruption tolerance on the internet. *IEEE Transactions on Mobile Computing*, 13(8):1668–1680, 2014.

[KHBL13] Chaehwan Kim, Hyunwoo Hwang, Jung-Woo Baik, and Kyung-Geun Lee. Multicast based proxy mobile ipv6 for inter-domain handover. *Mathematical and Computer Modelling*, 57(11):2863 – 2872, 2013. Information System Security and Performance Modeling and Simulation for Future Mobile Networks.

[KJKK08] B. Kim, Y. Jung, I. Kim, and Y. Kim. Enhanced fmipv4 horizontal handover with minimized channel scanning time based on media independent handover (mih). In *NOMS Workshops 2008 - IEEE Network Operations and Management Symposium Workshops*, pages 52–55, 2008.

[KK17] Darius Kalibatas and Vytautas Kovaitis. Selecting the most effective alternative of waterproofing membranes for multifunctional inverted flat roofs. *Journal of Civil Engineering and Management*, 23:1–11, 04 2017.

[KMBWW09] Mansoor Kiani Moghadam, Stephen Bonsall, Jin Wang, and Alan Wall. Application of multiple attribute decision-making (madm) and analytical hierarchy process (ahp) methods in the selection decisions for a container yard operating system. *Marine Technology Society Journal*, 43:34–50, 06 2009.

[Kög13] Jochen Kögel. *One-way delay measurement based on flow data in large enterprise networks.* Univ. Stuttgart, Inst. für Kommunikationsnetze und Rechnersysteme, 2013.

[KYVL19] BrunoY.L. Kimura, RobertoS. Yokoyama, LeandroA. Villas, and AntonioA.F. Loureiro. Mobility-aware application protocols. *Ad Hoc Networks*, 83:198 – 216, 2019.

[LL15] Douzhe Li and Zhao Li. *Optimization and Enhancement of MIPv6 in ATN*, pages 13–42. 08 2015.

[LLIS99] B. Landfeldt, T. Larsson, Y. Ismailov, and A. Seneviratne. Slm, a framework for session layer mobility management. In *Proceedings Eight International Conference on Computer Communications and Networks (Cat. No.99EX370)*, pages 452–456, 1999.

[LO13] Nicolas Larrieu and Philippe Owezarski. *Metrology of Internet Networks*, pages 101–117. 02 2013.

[MCdlO+07] Telemaco Melia, Daniel Corujo, Antonio de la Oliva, Albert Vidal, R Aguiar, and Ignacio Soto. Impact of heterogeneous network controlled handovers on multi-mode mobile device design. In *2007 IEEE Wireless Communications and Networking Conference*, pages 3884–3889. IEEE, 2007.

[McP16] T. McParland. Multihoming in the atn/ips. In *2016 Integrated Communications Navigation and Surveillance (ICNS)*, pages 2B2–1–2B2–11, April 2016.

[MDLOS+06] Telemaco Melia, Antonio De La Oliva, Ignacio Soto, Carlos J Bernardos, and Albert Vidal. Wlc34-2: Analysis of the effect of mobile terminal speed on wlan/3g vertical handovers. In *IEEE Globecom 2006*, pages 1–6. IEEE, 2006.

[MFOO03] A. Matsumoto, K. Fujikawa, Y. Okabe, and M. Ohta. Multihoming support based on mobile node protocol lin6. In *2003 Symposium on Applications and the Internet Workshops, 2003. Proceedings.*, pages 204–207, 2003.

[MGS20] Nils Mäurer, Thomas Gräupl, and Corinna Schmitt. L-band Digital Aeronautical Communications System (LDACS). Internet-Draft draft-maeurer-raw-ldacs-06, Internet Engineering Task Force, October 2020. Work in Progress.

[MJHN08] Robert Moskowitz, Petri Jokela, Tom Henderson, and Pekka Nikander. Host Identity Protocol. RFC 5201, April 2008.

[MS16] Dimitrios Mitrakos and Evangelos Spyrou. Hidden markov model traffic characterisation in wireless networks. pages 78–85, 01 2016.

[MT19] D. Madhubabu and A. Thakre. Long-short term memory based channel prediction for siso system. In *2019 International Conference on Communication and Electronics Systems (ICCES)*, pages 1–5, 2019.

[MTG14] Navitha Mariappan, R. Tamijetchelvy, and Sivaradje Gopalakrishnan. Robust vertical handover scheme using ieee 802.21 media independent handover. 04 2014.

[MTK+11] Nicolas Montavont, George Tsirtsis, Koojana Kuladinithi, Gerardo Giaretta, and Hesham Soliman. Flow Bindings in Mobile IPv6 and Network Mobility (NEMO) Basic Support. RFC 6089, January 2011.

[NVAH08] Pekka Nikander, Christian Vogt, Jari Arkko, and Tom Henderson. End-Host Mobility and Multihoming with the Host Identity Protocol. RFC 5206, April 2008.

[OMN] OMNeT++.

[Org00] International Civil Aviation Organization. Manual on hf data link, 2000. Doc 9741.

[Org01] International Civil Aviation Organization. Manual on vhf digital link (vdl) mode 2, 2001. Doc 9776.

[Org05] International Civil Aviation Organization. Icao annex 10. November 2005.

[Org09] International Civil Aviation Organization. Manual for the atn using ips standards and protocols (doc 9896), 2009.

[OVF16] J. Orimolade, N. Ventura, and O. Falowo. Andsf-based wlan offloading in the evolved packet system (eps). In *2016 18th Mediterranean Electrotechnical Conference (MELECON)*, pages 1–6, 2016.

[PAJ04] Charles E. Perkins, Jari Arkko, and David B. Johnson. Mobility Support in IPv6. RFC 3775, June 2004.

[PKLS07] Chang-Hyun Park, Sang-Won Kim, Sun-Min Lim, and Myung-Sun Song. Hmm based channel status predictor for cognitive radio. In *2007 Asia-Pacific Microwave Conference*, pages 1–4. IEEE, 2007.

[PP09] Esa Piri and Kostas Pentikousis. Ieee 802.21: Media independent handover services. *The Internet Protocol Journal*, 12(2):7–27, 2009. Project code: 19996.

[PTS+19] D. S. Ponchak, F. L. Templin, G. Sheffield, P. Taboso, and R. Jain. Advancing the standards for unmanned air system communications, navigation and surveillance. In *2019 IEEE Aerospace Conference*, pages 1–9, 2019.

[Rab89] L. R. Rabiner. A tutorial on hidden markov models and selected applications in speech recognition. *Proceedings of the IEEE*, 77(2):257–286, 1989.

[Rah15] Ahmad Rahil. *Gestion du Handover dans les réseaux hétérogènes mobiles et sans fil*. Theses, Université de Bourgogne, March 2015.

[rfc80] User Datagram Protocol. RFC 768, August 1980.

[rfc81] Transmission Control Protocol. RFC 793, September 1981.

[rfc89] Border Gateway Protocol (BGP). RFC 1105, June 1989.

[Rib96] Rita Almeida Ribeiro. Fuzzy multiple attribute decision making: a review and new preference elicitation techniques. *Fuzzy sets and systems*, 78(2):155–181, 1996.

[RJS+19] Vishal Rathod, Natasha Jeppu, Samanvita Sastry, Shruti Singala, and Mohit P. Tahiliani. Cocoa++: Delay gradient based congestion control for internet of things. *Future Generation Computer Systems*, 100:1053 – 1072, 2019.

[RMS+14] L. Z. Ribeiro, L. C. Monticone, R. E. Snow, F. Box, R. Apaza, and S. Bretmersky. A framework for dimensioning vdl-2 air-ground networks. In *2014 Integrated Communications, Navigation and Surveillance Conference (ICNS) Conference Proceedings*, pages Q3–1–Q3–14, April 2014.

[SHB14] Zach Shelby, Klaus Hartke, and Carsten Bormann. The Constrained Application Protocol (CoAP). RFC 7252, June 2014.

[SIM] Simulte.

[SKTY06] Sangheon Pack, Kunwoo Park, Taekyoung Kwon, and Yanghee Choi. Samp: scalable application-layer mobility protocol. *IEEE Communications Magazine*, 44(6):86–92, 2006.

[SS06] M. Schnell and S. Scalise. Newsky - a concept for networking the sky for civil aeronautical communications. In *2006 ieee/aiaa 25TH Digital Avionics Systems Conference*, pages 1–6, 2006.

[SSB03] Jon Salz, Alex Snoeren, and Hari Balakrishnan. Tesla: A transparent, extensible session-layer architecture for end-to-end network services. 02 2003.

[SSBG+20] Ruxandra Stoean, Catalin Stoean, Roberto Becerra-García, Rodolfo García-Bermúdez, Miguel Atencia, Francisco García-Lagos, Luis Velázquez-Pérez, and Gonzalo Joya. A hybrid unsupervised—deep learning tandem for electrooculography time series analysis. *PLOS ONE*, 15(7):1–15, 07 2020.

[SUM] Sumo.

[SWYS10] H. Si, Y. Wang, J. Yuan, and X. Shan. Mobility prediction in cellular network using hidden markov model. In *2010 7th IEEE Consumer Communications and Networking Conference*, pages 1–5, 2010.

[TKG10] V. Tiwari, S. Kansal, and A. Gaiwak. Performance evaluation of tcp variants using media independent handover in heterogeneous network. In *2010 International Conference on Computer and Communication Technology (ICCCT)*, pages 367–370, 2010.

[TPL+18] Alexandre Tran, Alain Pirovano, Nicolas Larrieu, Alain Brossard, and Stéphane Pelleschi. IP Mobility in Aeronautical Communications. In *Nets4, 13th International Workshop on Communication Technologies for Vehicles, Nets4Aircraft and UAV session*, volume Lecture Notes in Computer Science of *Communication Technologies for Vehicles - 13th International Workshop, Nets4Cars/Nets4Trains/Nets4Aircraft 2018*, pages pp 16–26 / ISBN 978–3–319–90370–5, Madrid, Spain, May 2018. Springer.

[TSD+20] Fred Templin, Greg Saccone, Gaurav Dawra, Acee Lindem, and Victor Moreno. A Simple BGP-based Mobile Routing System for the Aeronautical Telecommunications Network. Internet-Draft draft-ietf-rtgwg-atn-bgp-06, Internet Engineering Task Force, June 2020. Work in Progress.

[VSLBR17] Antonio Virdis, Giovanni Stea, Stefano La Barbera, and Winkler Roberto. Sapient-simulator modelling and architecture. In *23rd Ka and Broadband Communications Confernece*, volume 2017. FGM Events LLC, 2017.

[WL13] Shu-Ping Wan and Deng-Feng Li. Fuzzy linmap approach to heterogeneous madm considering comparisons of alternatives with hesitation degrees. *Omega*, 41(6):925–940, 2013.

[WTD+09] Ryuji Wakikawa, George Tsirtsis, Vijay Devarapalli, Thierry Ernst, and Kenichi Nagami. Multiple Care-of Addresses Registration. RFC 5648, October 2009.

[WZYZ08] Y. Wang, Y. Zhou, J. Yuan, and P. Zhang. An enhanced media independent handover framework for heterogeneous networks. In *VTC Spring 2008 - IEEE Vehicular Technology Conference*, pages 2306–2310, 2008.

[Yav15] Mahmut Yavuz. The application of the analytic hierarchy process (ahp) and yager's method in underground mining method selection problem. *International Journal of Mining, Reclamation and Environment*, 29(6):453–475, 2015.

[YBK+06] Yoon Young An, Byung Ho Yae, Kang Won Lee, You Ze Cho, and Woo Young Jung. Reduction of handover latency using mih services in mipv6. In *20th International Conference on Advanced Information Networking and Applications - Volume 1 (AINA'06)*, volume 2, pages 229–234, 2006.

[YMW+20] Jining Yan, Lin Mu, Lizhe Wang, Rajiv Ranjan, and Albert Y Zomaya. temporal convolutional networks for the advance prediction of enso. *Scientific Reports*, 10(1):1–15, 2020.

[Zha04] Wenhui Zhang. Handover decision using fuzzy madm in heterogeneous networks. In *2004 IEEE Wireless Communications and Networking Conference (IEEE Cat. No. 04TH8733)*, volume 2, pages 653–658. IEEE, 2004.

[ZM02] Victor C. Zandy and Barton P. Miller. Reliable network connections. In *Proceedings of the 8th Annual International Conference on Mobile Computing and Networking*, MobiCom '02, page 95–106, New York, NY, USA, 2002. Association for Computing Machinery.

[ZSZ+04] Jie Zhang, Dan Shen, Guodong Zhou, Jian Su, and Chew-Lim Tan. Enhancing hmm-based biomedical named entity recognition by studying special phenomena. *Journal of Biomedical Informatics*, 37(6):411 – 422, 2004. Named Entity Recognition in Biomedicine.

Appendix A

Study of the VDLm2 protocol delay

In the chapter 2, we have developed a framework in which we implement our mobility protocol. However, this framework doesn't take into account the delay encountered at the Link access layer. Therefore, we are interested here in modeling this delay for the VDLm2 link access technology, which is the current VHF technology in aeronautical networks. This delay is then taken into account to compute the handover delay of our mobility protocol. Our study is performed in OMNeT++, with the VDLm2 model provided by the ENAC lab.

Case scenario

We consider a VDLm2 ground station and N aircraft that are using this station as their point of access to the ATN/IPS, as shown in the Figure 36. Each aircraft send packets to the ground station, and reversely, with an IAT following an exponential law of $40s$. This interval has been chosen to reach the maximal occupancy rate in the VDLm2 cell when the number of aircraft equals to the PIAC in the Maastricht area, which is one of the most crowded area in Europe. The simulation duration is 10h to get enough data for the analysis.

Model of the VDLm2 delay

The VDLm2 link technology is based on a random policy and the channel occupancy for the transmission of the packet. Therefore, it is hard to know in advance the delay induced at the Link access layer. In the scenario described above, we look at this delay in both the aircraft and the ground station. We can neglect the propagation delay in this case which is around a millisecond for the considered distance. An example of the distribution of the delay perceived by uplink and downlink packets is illustrated in the Figure 37, with $N = 50$ and $N = 100$. From this graph, we can make the approximate that the distribution of the delay follows an exponential law with a λ equals to the average of the delay (red line in the Figure 37). So we assume that for each case scenario with a different value of N, the delay induced by the Link access layer follow an exponential law, and we just need to determine the mean value of this delay. In the following, we vary the value of N ranging from 10 to 250 and look at the mean value

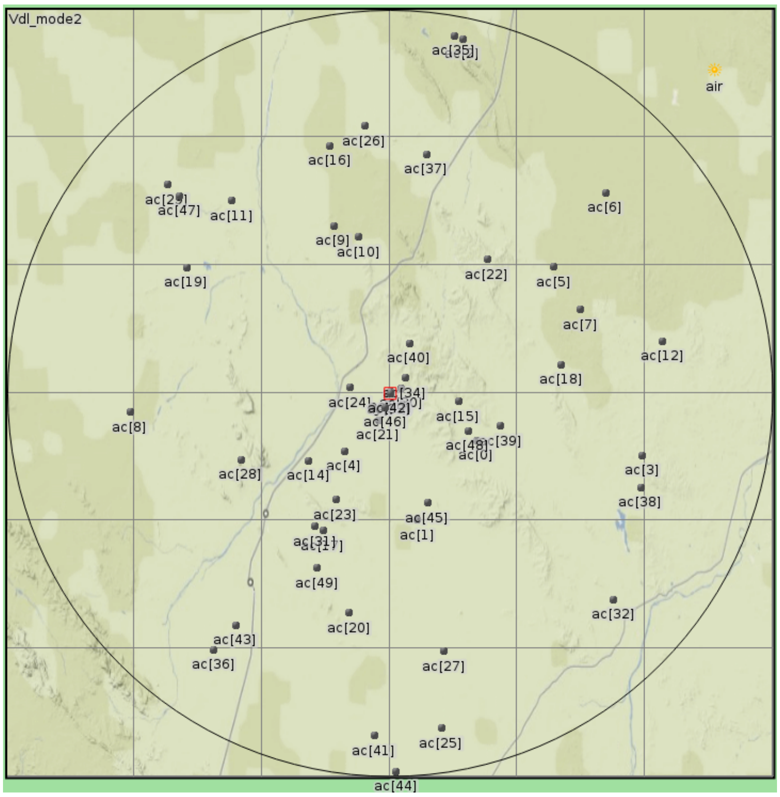
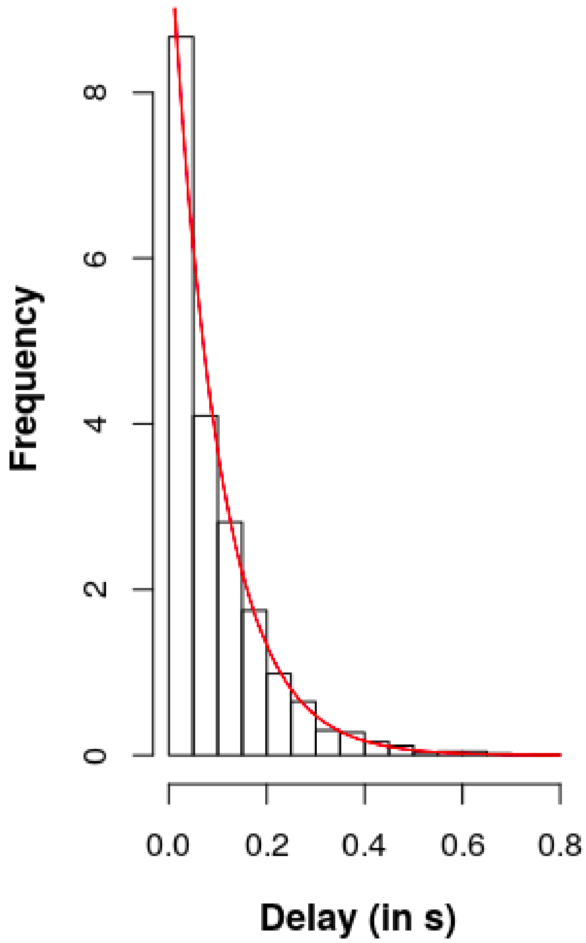


Figure 36: VDLm2 cell with N aircraft and a ground station

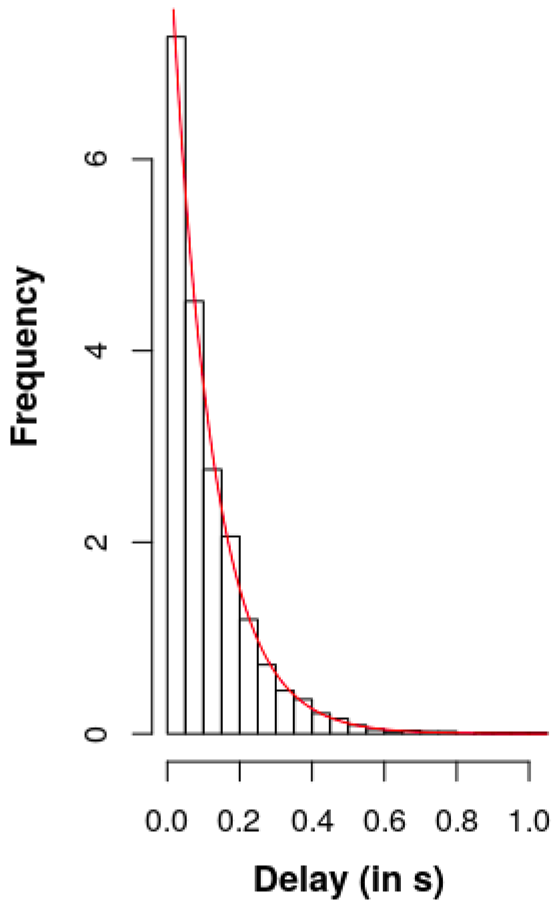
of the delay for uplink and downlink packets. The results are shown in the Figure 38. We can find a polynomial approximation to estimate the average delay of the packets based on the number of aircraft present in the VDLm2 cell as illustrated in 38a and 38b. The average delay for downlink packets is approximated with a polynomial of order 3 and for uplink packets with a polynomial of order 5.

Conclusion

This simple scenario allows to determine a model of the delay induced by the VDLm2 link technology. Indeed, based on the number of aircraft considered in the cell, we are able to approximate the average delay and thus the distribution of the packet delay with the exponential law.

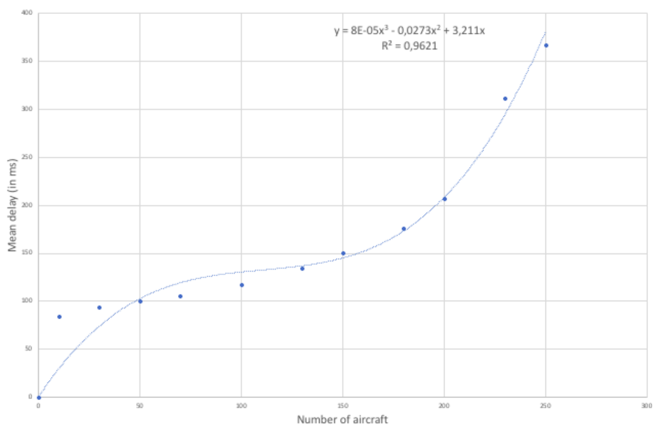


(a) N = 50

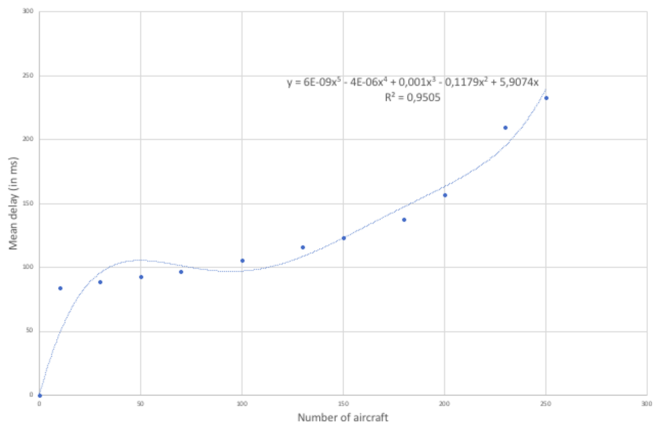


(b) N = 100

Figure 37: Delay distribution for uplink packets



(a) Average delay for downlink packets at the Link access layer



(b) Average delay for uplink packets at the Link access layer

Figure 38: Average VDLm2 link access delay with respect to the number of aircraft