# Onboard IP router for critical aeronautical communications in a heterogeneous environment

## PhD Defense

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Janvier 2021

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# Outline

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# to respond to the air traffic growth

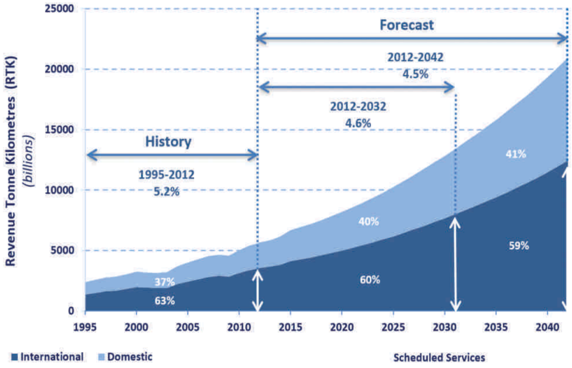


Figure: ICAO air traffic history and prediction (July 2016 report)

## Consequences:

- voice channel congestion
- decrease aircraft separation standard

## Solution

- need for new datalink communication systems to improve the safety

# Outline

# Different types of onboard applications (ICAO annex 10)

## Non safety-related applications

- APC (Aircraft Passenger Communications): video, calls , ...
- AAC (Airlines Administrative Communications): crew/passenger information

## Safety-related applications

- ATSC (Air Traffic Services Communications): for air traffic control, navigation, weather forecast, aircraft location.
- AOC (Airlines Operational Communications): related to aircraft operability, maintenance, so on.

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# Outline

# ATN[2] subnetworks

| Systems | Capacity | Range/Coverage |
|---|---|---|
| VDLm2[1] | 31.5 kbps per station | 200km |
| HFDL | 1.8 kbps per station | 2500 km |
| Iridium | 2.4 kbps per aircraft | global |
| Inmarsat H+ | 100 kbps in total | latitude $< 80°$ |

Table: Characteristics of the current air-ground datalink subnetworks

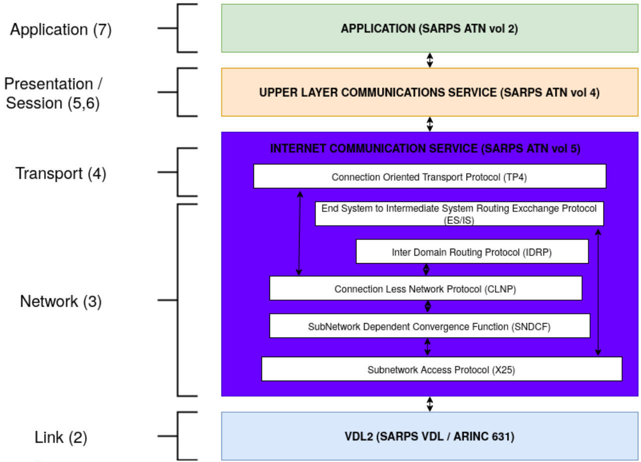
| Systems | Capacity | Range/Coverage |
|---|---|---|
| LDACS | 2.3 Mbps per station | 200 km |
| AeroMACS | 30 Mbps per station | short range |
| Iridium Next | 100 kbps in total | global |
| Inmarsat SBB | 432 kbps in total | latitude $< 80$ ° |

Table: Characteristics of the future air-ground datalink subnetworks in the ATN/IPS

[2] Aeronautical Telecommunication Network
[1] VHF Datalink mode 2

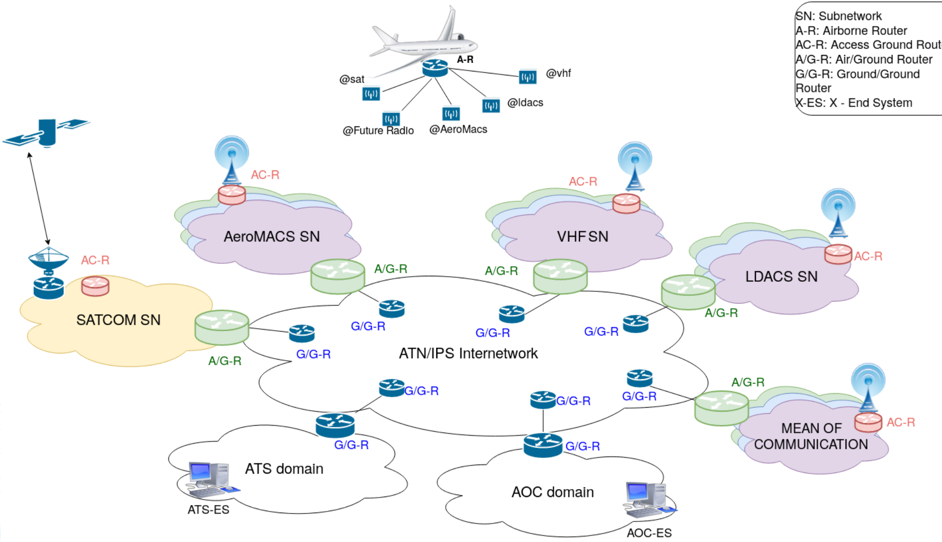
# Outline

# The ATN/OSI network (from the 2000s)



# The ATN/IPS network (from end of the 2020s)

SN: Subnetwork
A-R: Airborne Router
AC-R: Access Ground Router
A/G-R: Air/Ground Router
G/G-R: Ground/Ground Router
X-ES: X - End System



# Challenges in the new ATN/IPS

## Addressing

To assign a unique global **@IPv6** to the aircraft bind to its **@ICAO**.

## IP Mobility

To handle seamlessly the aircraft reachability while it is moving between subnetworks.

## Multilink

To be able to use the simultaneous air/ground links to improve the QoS.

## Security

To provide different layers of security for the end-to-end communication.

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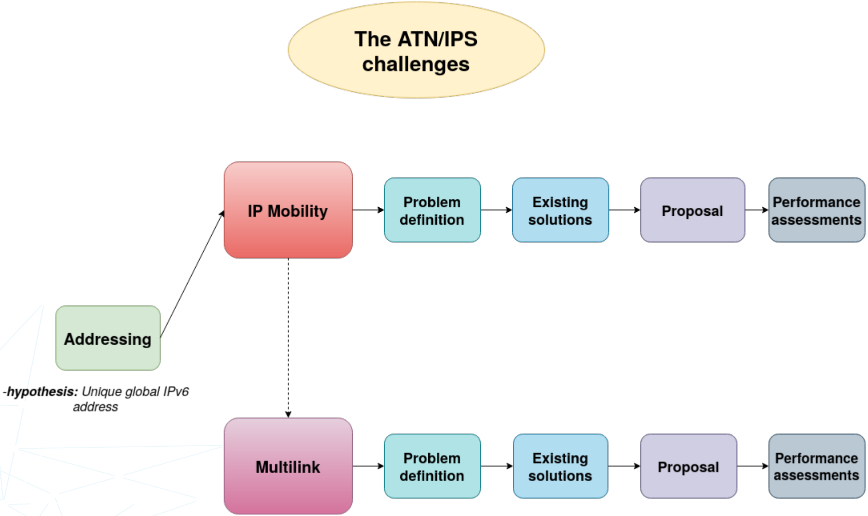
# Organization of the research



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# The ATN/IPS network: a heterogeneous environment

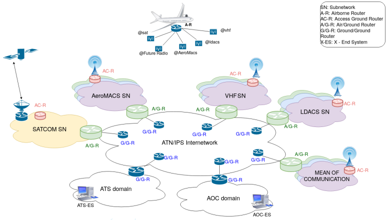


Figure: The ATN/IPS infrastructure

| Type | Horizontal | Vertical |
| --- | --- | --- |
| Intra-domain | DSP A LDACS / DSP A LDACS | DSP A LDACS / DSP A VDLm2 |
| Inter-domain | DSP A LDACS / DSP B LDACS | DSP A LDACS / DSP B VDLm2 |

Table: Handover scenarios

## Challenge

To handle seamlessly the different handover scenarios by keeping the **same aircraft IPv6 address**.

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# Network IP mobility solutions assessment

| Protocols | HIP | BGP | MIPv6 | PMIPv6 | G-LISP[3] |
|---|---|---|---|---|---|
| Session continuity | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ |
| Inter-domain handover | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\ominus$ | $\bigoplus$ |
| Intra-domain handover | $\ominus$ | $\ominus$ | $\ominus$ | $\bigoplus$ | $\ominus$ |
| 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: Candidate protocols to fulfill mobility requirements for the ATN/IPS (optimal $\bigoplus$, acceptable $\oplus$, average $\odot$ and non compliant $\ominus$)

[3] Ground- Locator/Identifier Separation Protocol

# Proposed solution for ATN/IPS

| Protocols | HIP | BGP | MIPv6 | PMIPv6 | G-LISP | P-LISP[4] |
|---|---|---|---|---|---|---|
| Session continuity | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ |
| Inter-domain handover | $\bigoplus$ | $\bigoplus$ | $\bigoplus$ | $\ominus$ | $\bigoplus$ | $\bigoplus$ |
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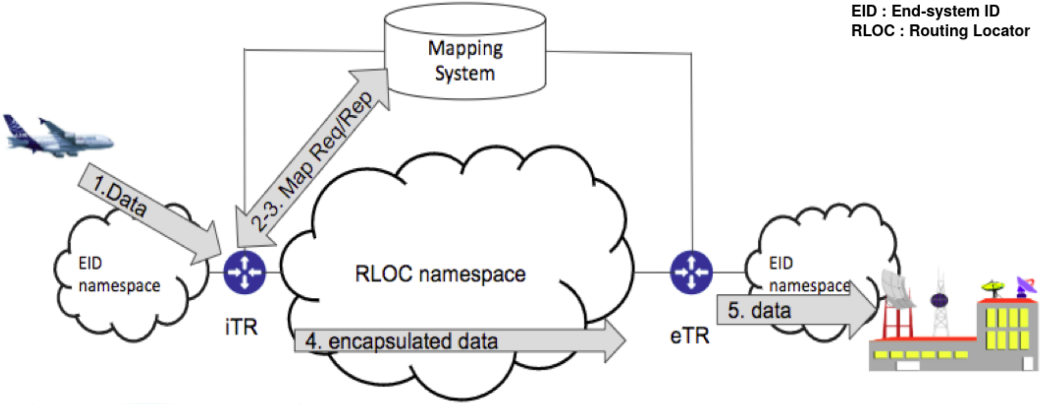
Table: Candidate protocols to fulfill mobility requirements for the ATN/IPS (optimal $\bigoplus$, acceptable $\oplus$, average $\odot$ and non compliant $\ominus$)

[4] Proxy-LISP

# Outline

# P-LISP Packet Routing

EID : End-system ID
RLOC : Routing Locator

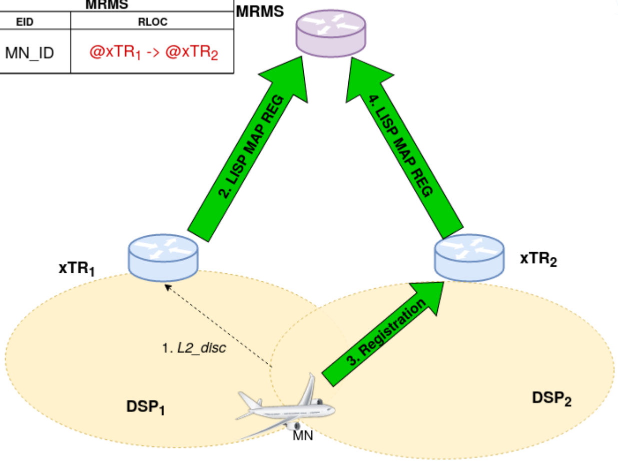


# P-LISP inter-domain handover management

## Network entities

- **Mapping system** (MRMS server): to **maintain the mapping** between the MN's RLOC and the MN's EID. **Publish/subscribe mechanism** added for EID-to-RLOC update announcement.
- **Tunnel Router** (xTR): to inform the MRMS of the **MN location** and to **forward packets** from/to the MN by **UDP encapsulation**.

| MRMS | |
|---|---|
| EID | RLOC |
| MN_ID | @$xTR_1$ -> @$xTR_2$ |

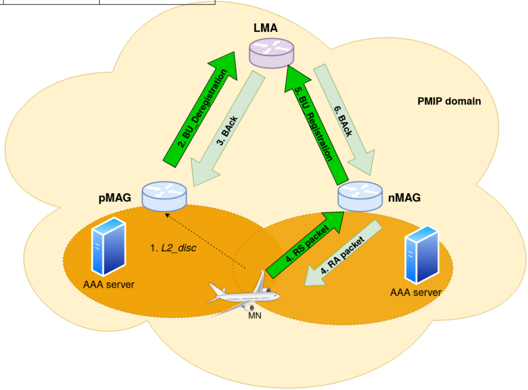


# P-LISP intra-domain handover management

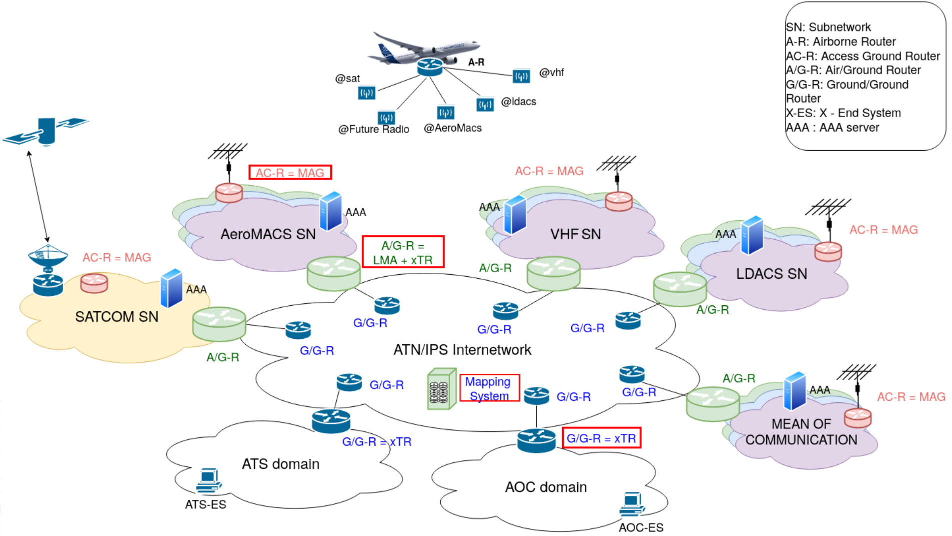
## Network entities

- **Local Mobility Anchor** (LMA):
  - forwards packets outside the domain and to the MN's attached MAG.
  - attributes a HNP (Home Network Prefix) to the aircraft and **share this information via multicast group**.
- **Mobile Access Gateways** (MAGs): interconnect the MN to the subnetwork and manage the MN's signalling.

| LMA binding cache | | |
|---|---|---|
| ID | HNP | pCoA |
| MN_ID | @pref_HNP | @pMAG -> @nMAG |



# Deployment of the solution for the ATN/IPS



# Handover sequence diagrams for P-LISP

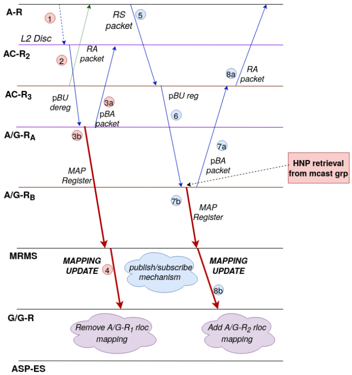



Figure: Inter-domain handover

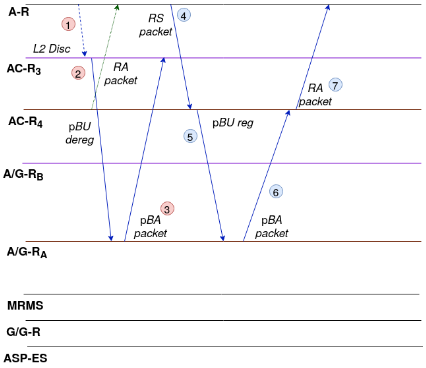



Figure: Intra-domain handover

# Outline

# Handover scenarios

## Simulation parameters

- Aircraft at speed 250 m/s
- 2 service providers
- overlapping area: 50km
- inter+intra-domain handover
- simulation time : 20min

## MIPv6/PMIPv6 comparison

- end-to-end delay
- handover delay

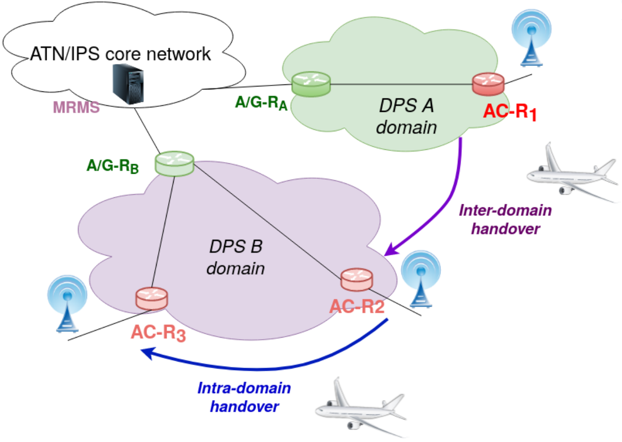



Figure: Test scenario

# Development of the framework in OMNeT++

## Protocol Development

- ATS traffic model from NASA study. [5]
- G-LISP for IPv6 based on ANSA framework
- PUSH mechanism for MRMS
- PMIPv6 based on xMIPv6 of the INET framework
- multicast group for HNP
- Layer 2 handover management
- simulation of Vdlm2-link delay

| | |
|---|---|
| Application Layer | **ATS Traffic** |
| Transport Layer | UDP |
| Network layer | IPv6 / **P-LISP** / **PMIPv6** |
| Link layer | CSMA / **L2 handover manager** |
| Physical Layer | Ideal Radio |

[5] Ribeiro and al. *"A framework for dimensionning vdl-2 air-ground network"*

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# End-to-end delay

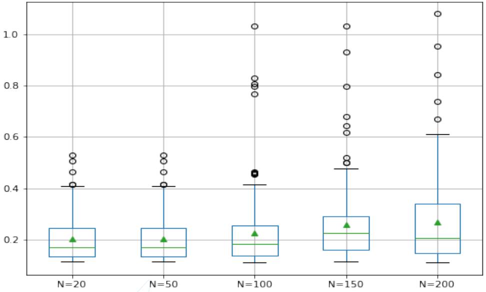



Figure: E2E delay (s) wrt cell load for P-LISP

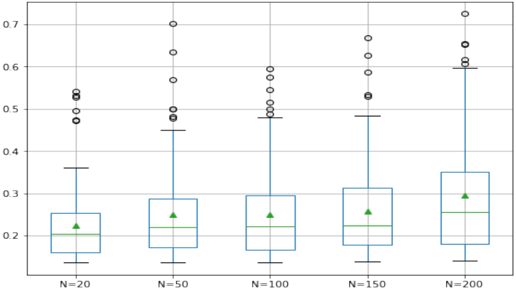
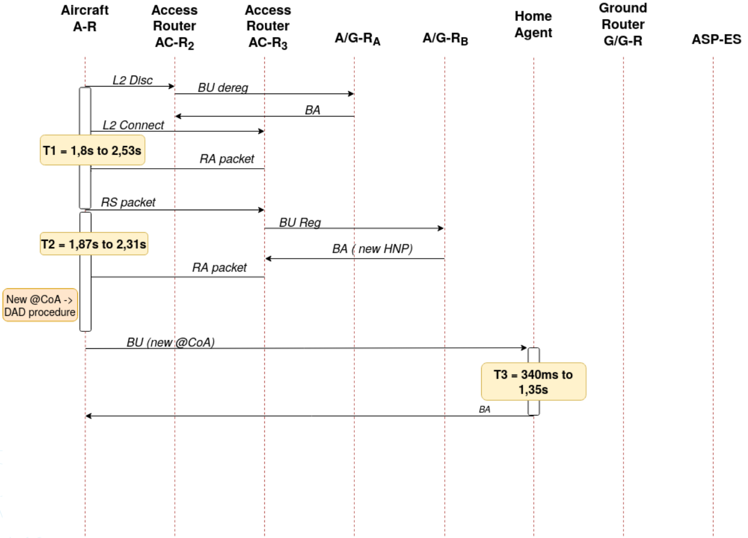



Figure: E2E delay (s) wrt cell load for MIP/PMIP

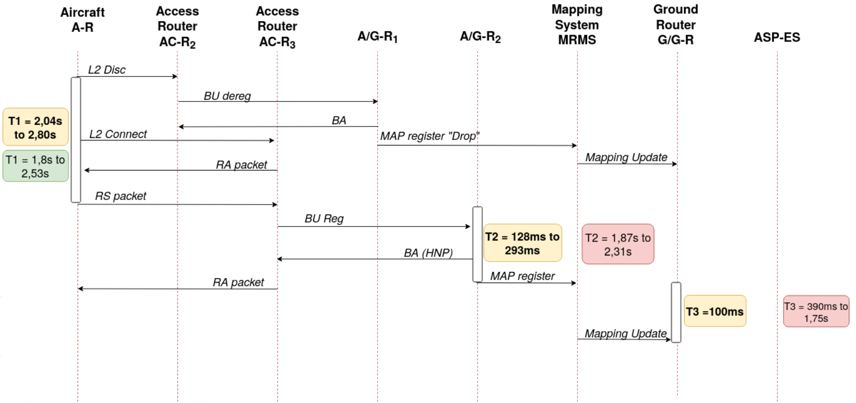
## Results

- Packets are forwarded via an **optimal route** instead of the MIP/PMIP solution.

# Inter-domain handover delay for the MIPv6/PMIPv6



# Inter-domain handover delay for the P-LISP



# Comparison with standard requirements

## End-to-end delay

- Delay respected in best case scenarios (aircraft and CN in same continent)

| Service | Delay (in s) | Msg exchanged | e2e delay P-LISP (in s) | e2e delay MIP/ PMIPv6 (in s) |
|---|---|---|---|---|
| ACL | 3.0 | 4 | 0.78 | 0.86 |
| COTRAC | 5.0 | 7 | 1.37 | 1.51 |
| FLTPLAN | 30 | 18 | 3.51 | 8.87 |

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

## Handover delay

- P-LISP reduces by twice the **handover delay** (from 6.2s to 3.15s)
- For almost all types of applications, the delay is respected even after a handover. (COTRAC: 1.37s + 3.15s = 4.52s)

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# Conclusions

## Development of an IP mobility solution for ATN/IPS

1. P-LISP based on the G-LISP enhanced with the PMIPv6 and routing update mechanism.
2. No major flaws:
   - adequate for both intra and inter-domain handovers.
   - signalling is minimum over the radio links.
   - no need for additional protocols onboard.
3. Development of a simulation model under OMNeT++.
4. Performs better than a MIPv6/PMIPv6 approach.

# Outline

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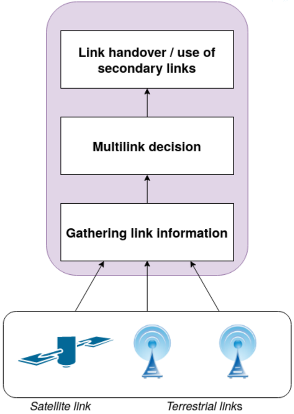
# Multilink properties

## Why multilink is necessary ?

- To offload the traffic when congestion occurs (use of secondary links).
- To avoid the delay introduced by the link establishment when a vertical handover occurs.
- To better manage the overall network resource.

## Multilink (ML) algorithm

- **Step 1**: Retrieves link information for the decision algorithm
- **Step 2**: Decision algorithm (fuzzy logic, MADM, Game theory, ...)
- **Step 3**: Handover/Offload execution (mobility protocols)



# Outline

# Gathering link quality information

## In the literature

- the 802.21 Media Independent Handover (MIH)
- the Access Network Discovery and Selection Function (ANDSF)

## Link information available in aeronautical networks

- VDLm2: **SQP parameter** (signal quality)
- others (HF, Satcom): **Link status** (ON/OFF)

## Requirements for the ATN/IPS

- Dynamic link selection taking into account the quality of the subnetwork access.
- Compatible with all the existing and the future subnetwork accesses.
- With a low cost implementation onboard.

# Outline

# Retrieve the state of the radio link via the RTT

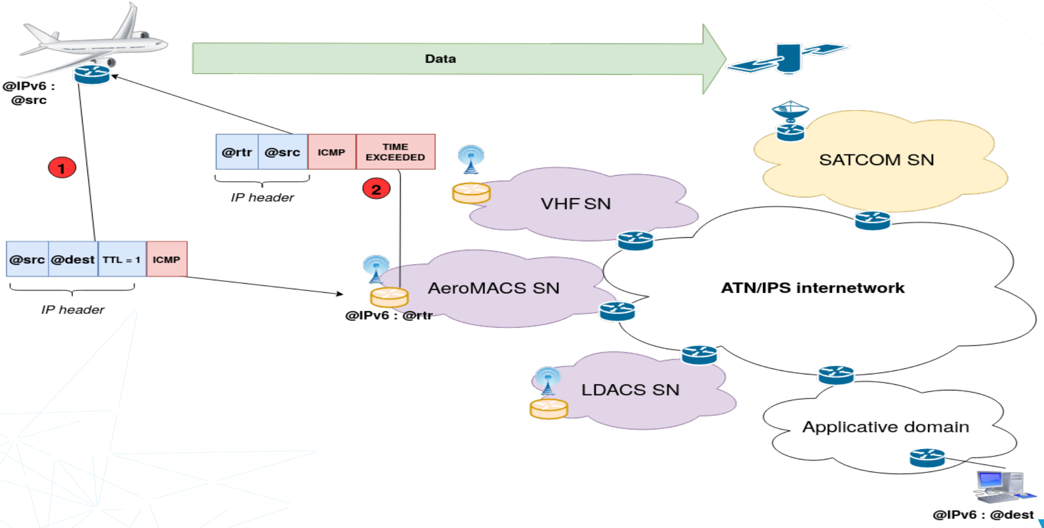



Figure: Secondary link probing

# Outline

# 3 methods to determine the link quality

**Goal**: predict link quality in terms of the used capacity (GOOD-MEDIUM-BAD)
**Input** : past values of the RTTs

## Hidden Markov Model (HMM)

- learning parameters: matrix A and B, initial probability
- learning method: forward algorithm

## Threshold based algorithm

- 2 features: a current value and a historical value of the RTTs
- learning parameters : feature(min,max) through link technology knowledge

## Long Short Term Memory Neural Network(LSTM)

- learning method: supervised learning
- architecture: a single layer for 1 step prediction, and a 2-layer for multiple step prediction

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# Simulation scenario

## Based on air traffic replays

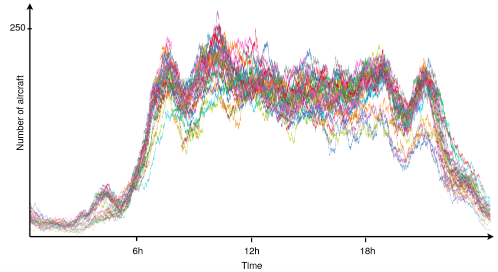


Figure: Air traffic in february 2020 over the Maastricht region

## Link quality assessment

- Cell's used capacity is directly linked to the number of aircraft
- daily scenario
- **SAPIENT framework**: collaboration with University of Pisa
- Link technology assessment: LDACS and VDLm2
- Supervised training: label data from link access technology

# Probe inter-arrival time dimensioning

| Traffic type | Packet per sec | packet size (B) | throughput (B/s) | % of bandwidth 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: LDACS scenario

| Traffic type | Packet per sec | packet size (B) | throughput (B/s) | % of bandwidth 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: VDLm2 scenario

# The HMM method: results

## Link state autocorrelation

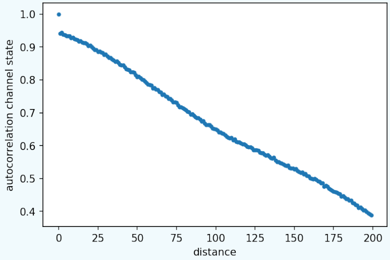


Figure: VDLm2 case

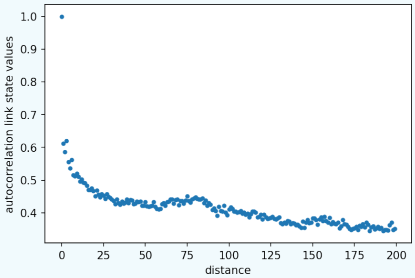


Figure: LDACS case

Not able to predict the quality of the link in both scenarios.

# Threshold algorithm: VDLm2 result

## Classification over 3 link states (GOOD - MEDIUM - BAD)

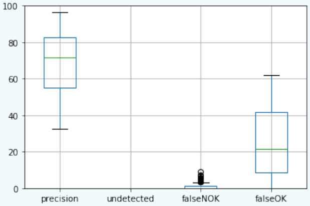


Figure: Average RTT vs RTT

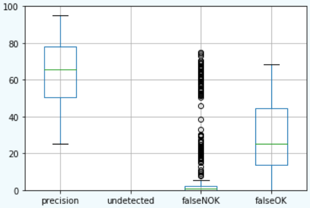


Figure: Exponential Weighted average($\alpha = 0.1$) vs RTT

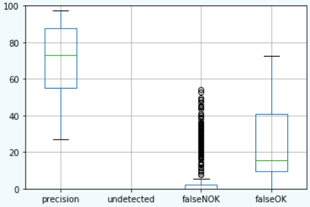


Figure: Rolling standard deviation vs RTT

The Rolling Standard deviation gets the best overall results.

# Comparison with the LSTM model

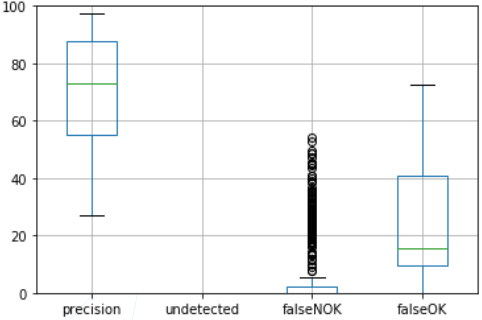


Figure: Threshold-based result

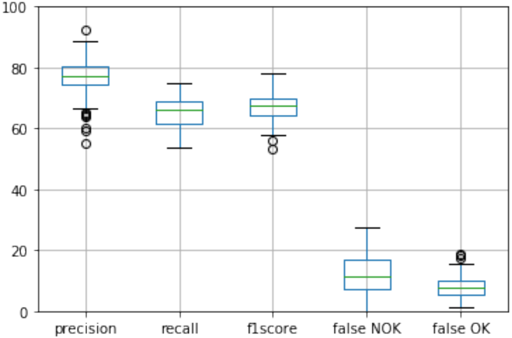


Figure: LSTM result

# Threshold algorithm: LDACS results

## 1NZQTH: metric based on the history of RTT

- $$\sigma(RTT) = \begin{cases} \frac{RTT(ms)-180}{60} & \text{if } RTT(ms) > 180 \\ 0 & \text{else.} \end{cases} \quad (1)$$
- 1NZQTH : first quantile of $\sigma(RTT)_i$ with a non zero value.

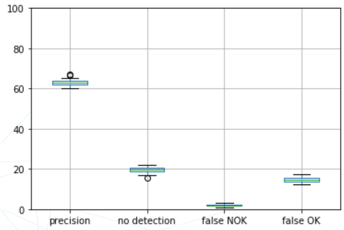


Figure: 1NZQTH vs RTT

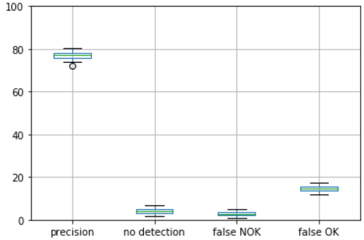


Figure: 1NZQTH vs average RTT

# Comparison with the LSTM model

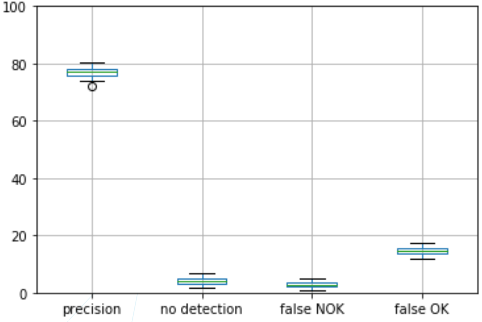


Figure: Threshold-based result

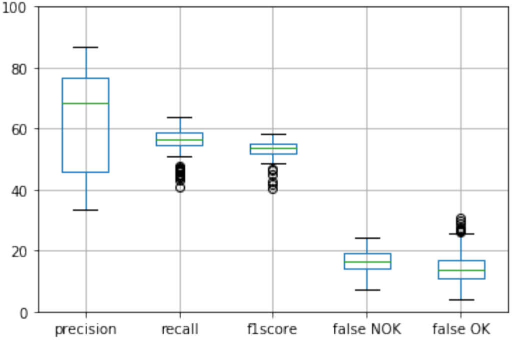


Figure: LSTM result

# LSTM for trend prediction

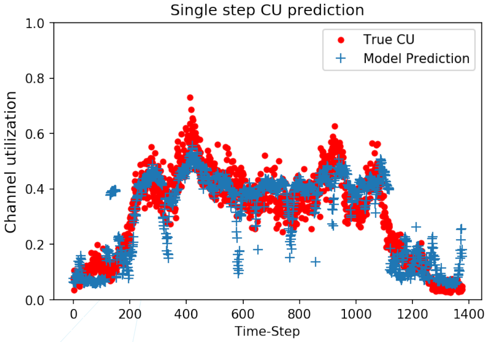


Figure: VDLm2 scenario

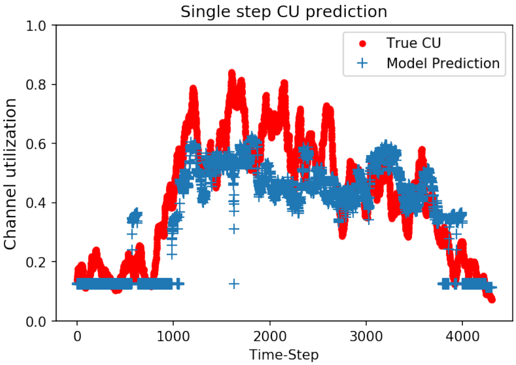


Figure: LDACS scenario

# LSTM for multi-step prediction results

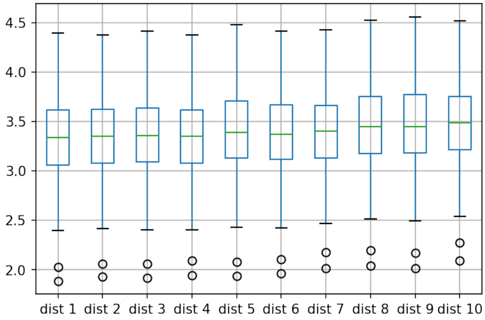


Figure: Euclidian distance wrt step prediction (VDLm2 scenario)

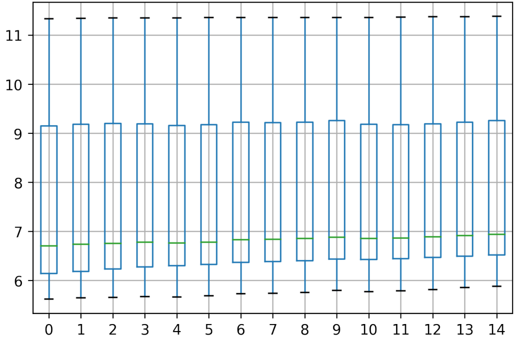


Figure: Euclidian distance wrt step prediction (LDACS scenario)

Performances are stable regarding the step prediction. A small degradation for the LDACS scenario.

# Outline

# Conclusions

## Enable the aircraft to assess the quality of secondary links

- With an active link probing method (ICMP packets).
- Three methods for link quality prediction:
  1. HMM: not suited due to the high data correlation.
  2. Threshold-based: good single prediction except for BAD link quality.
  3. LSTM: single prediction not so good but is able to predict the trend and over future states.
- **Recommendation for the ATN/IPS**: method 2 onboard the aircraft for its accuracy and low cost implementation.

Collins Aerospace
A United Technologies Company
TéSA
Telecommunications for Space and Aeronautics

# Outline

# Summary

## Aircraft IP mobility

- **P-LISP solution:** global solution for managing aircraft IP mobility with no major flaws.
- Implementation of mobility protocols in OMNeT++ dedicated framework.
- Better performances than the standard MIPv6/PMIPv6 for handover and end-to-end delay.

# Summary

## Aircraft IP mobility

- **P-LISP solution:** global solution for managing aircraft IP mobility with no major flaws.
- Implementation of mobility protocols in OMNeT++ dedicated framework.
- Better performances than the standard MIPv6/PMIPv6 for handover and end-to-end delay.

## Aircraft multilink properties

- Propose a way to provide link quality information to the onboard router, independent from the subnetworks access.
- Assess three statistical methods to predict the link quality.
- Implement our solution in a dedicated framework.
- Obtain interesting results that can be used for a multilink decision algorithm.

# Further work

## Around aircraft IP mobility

- Virtual interface needed for the vertical inter-domain handover.
- To port the solution to the SAPIENT framework.
- To define other scenarios for the performance assessments.

# Further work

## Around aircraft IP mobility

- Virtual interface needed for the vertical inter-domain handover.
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- To define other scenarios for the performance assessments.

## Around the multilink opportunities

- To extend our dataset with others air traffic data.
- A ground centralized approach to collect and share link information.
- Multilink decision algorithm with our link quality information.
- HMM of higher order for link prediction.

# Contributions

## International conferences

- **A. Tran**, A. Pirovano, N. Larrieu, A. Brossard and S. Pelleschi, "IP Mobility in Aeronautical Communications", Nets4 13th International Workshop on Communication Technologies for Vehicles Nets4Aircraft and UAV session ser. Communication Technologies for Vehicles – 13th International Workshop Nets4CarsINets4Trains/Nets4Aircraft 2018
- **A. Tran**, A. Pirovano and N. Larrieu, "Managing aircraft mobility in a context of the ATN/IPS network," 2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC), San Diego, CA, USA, 2019

## Journal paper

- **A. Tran**, A. Pirovano and N. Larrieu, "Air-ground link quality prediction in the ATN/IPS network", (submitted in *Journal of Aerospace Information systems, AIAA)*, Jan 2021)