Artificial Intelligence for Wireless Avionics Intra-Communications

Robles, Ramiro Samano; Venkatesha Prasad, R.; Arts, Ad; Rzymowski, Mateusz; Kulas, Lukasz

DOI
10.1007/978-3-031-54049-3_18

Publication date
2024

Document Version
Final published version

Published in
Studies in Computational Intelligence

Citation (APA)
Robles, R. S., Venkatesha Prasad, R., Arts, A., Rzymowski, M., & Kulas, L. (2024). Artificial Intelligence for Wireless Avionics Intra-Communications. In *Studies in Computational Intelligence* (pp. 331-352). (Studies in Computational Intelligence; Vol. 1147). Springer. https://doi.org/10.1007/978-3-031-54049-3_18

Artificial Intelligence for Wireless Avionics Intra-Communications

Ramiro Samano Robles, R. Venkatesha Prasad, Ad Arts,
Mateusz Rzymowski, and Lukasz Kulas

Abstract This chapter presents a summary of the description and preliminary results of the use case related to the implementation of artificial intelligence tools in the emerging technology called wireless avionics intra-communications (WAICs). WAICs aims to replace some of the cable buses of modern aircraft. This replacement of infrastructure leads to: (1) complexity reduction of future airplanes, (2) creation of innovative services where wireless links are more flexible than wireline links, and mainly (3) a considerable weight reduction, which in turn leads to fuel consumption efficiency, increase of payload, as well as range extension. Therefore, WAICs is expected to have a large impact on the aeronautics industry, propelling a new generation of greener, more efficient, and less expensive aeronautical services. However, there are still several reliability, trust, interoperability and latency issues that need to be addressed before this technology becomes commercial. It is expected that AI will boost the applicability of this technology, contributing to the realization of the concept of "*fly-by-wireless*".

R. S. Robles (✉)
Research Centre in Real-Time and Embedded Computing Systems, Polytechnic Institute of Porto,
Rua Alfredo Allen, 535, 4200-135 Porto, Portugal
e-mail: rasro@isep.ipp.pt

R. Venkatesha Prasad
Faculty of Engineering, Mathematics and Computer Science, Delft University of Technology,
Van Mourik Broekmanweg 6, 2628 XE, Delft, The Netherlands
e-mail: r.r.venkateshaprasad@tudelft.nl

A. Arts
NXP Semiconductors, High Tech Campus 46, 5656AE Eindhoven, The Netherlands
e-mail: ad.arts@nxp.com

M. Rzymowski · L. Kulas
Politechnika Gdańska, ul. Narutowicza 11/12, Gdańsk 80-233, Poland
e-mail: mateusz.rzymowski@pg.edu.pl

L. Kulas
e-mail: lukasz.kulas@eti.pg.gda.pl

M. Karner et al. (eds.), *Intelligent Secure Trustable Things*, Studies in Computational
Intelligence 1147, https://doi.org/10.1007/978-3-031-54049-3_18

Acronyms

Use the template *acronym.tex* together with the document class SVMono (monograph-type books) or SVMult (edited books) to style your list(s) of abbreviations or symbols.

Lists of abbreviations, symbols and the like are easily formatted with the help of the Springer Nature enhanced `description` environment.

AI	Artificial Intelligence
AFC	Active FLow Control
AFDX	Avionics Full-Duplex Switched Ethernet
ARINC	Aeronautical Radio, Incorporated
ATM	Air Traffic Management
AWGN	Additive White Gaussian Noise
BL	Boundary Layer
CAN	Controller Area Network
DEWI	Dependable Embedded Wireless Infrastructure
DoA	Direction of Arrival
FDTD	FInite Difference Time Domain
IEEE	Institute of Electrical and Electronics Engineers
InSecTT	Intelligent Secure Trustable Things
IoT	Internet of Things
ISO	International Standards Organisation
ITU	International Telecommunications Union
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
PL	Power Line
SCOTT	Secure Connected Trustable Things
TTP	Time-Triggered Protocol
UMTS	Universal Mobile Telecommunication System
WAICs	Wireless Avionics Intra-Communications
WiFi	Wiresless Fidelity
WSN	Wireless Sensor Networks

1 Introduction

The advent of the Internet-of-things (IoT) means that objects with embedded processing and networking capabilities will be exchanging information with cloud or edge infrastructure almost in real-time. It is expected that billions of devices will be connected to the cloud in the coming decades. Many of these connections are expected to be achieved by wireless links. In comparison with their wireline counterparts, wireless channels constitute much harsher and random propagation media. However, wireless technology provides several advantages, such as flexible deployment, reduced implementation times, mobility, and the ability to cover locations difficult to reach with cables [1]. In addition, it enhances end-user experience improving automatic commissioning, management, and configuration. Aeronautics provides a framework where wireless and wireline will experience a complex coexistence. Wireless technology is becoming more competitive, and new releases are quickly catching up with wireline technology. But wireline technology evolves too with more efficient power-line communication and higher levels of cross-talk reduction technology. Therefore, it is expected that the decision to use either cables or wireless links will become a complex task due to the multiple factors and criteria needed by future applications.

In avionics, wireless technology is well known for air traffic management (ATM), telemetry, aircraft-ground control, satellite communication/localization, inter-aircraft communications and radar. By contrast, intra-avionics communications have just recently gained attention. Conventionally, the main concerns with the use of wireless links on aircraft are related to reliability/safety critical operations, security, and interference to on-board systems. However, recent studies suggest that commercial technologies show low impact to on-board systems. This has paved the way for interesting wireless applications for aircraft, which have been called wireless avionics intra-communications (WAICs).

One major potential advantage of using wireless technology in aeronautics is the reduction of cables [2]. According to [3], helicopters carry almost 2,000 pounds of wires. It is estimated that the use of wireless will bring a 12% reduction in terms of fuel consumption [4]. Cabling tasks cost nearly 2,200 dollars per kg of aircraft [5]. Estimated savings can reach 14–60 millions of dollars per aircraft [5]. Electrical wiring problems cause on average two in-flight fires every month as well as thousands of mission aborts and lost mission hours per year [6]. Each year, one to two million man-hours are spent by navy in finding and fixing wiring problems [7]. Damages on cables can affect not only the system related to the faulty wire, but also contiguous systems [8]. It is also estimated that 13% of an aircraft operation cost is related to maintenance, reparation and overhaul. Wireless nodes can also cover locations not easily reached by cables. Therefore, wireless is expected to bring considerable gains to the industry in terms of reduction of wires, flexible designs, and improved troubleshooting. This has been called “fly-by-wireless” [9].

An attractive use of wireless technology in aeronautics is sensing. Recent advances have provided a reliable, cost-effective, self-organized, ad-hoc, and flexible networking technologies [10, 11]. Furthermore, WSN technology provides with self-configuration, RF tolerance, and maintenance troubleshooting [8]. In critical applications though, wireless links cannot completely replace cables due to the high reliability requirement. However, they can act as redundant links, thus increasing reliability and flexible design.

Despite recent advances in the feasibility testing of this technology, WAICs is not yet commercial in the aeronautics industry. Multiple tests have been done proving that wireless can replace successfully cables and even the full buses of different types of aircraft in flight conditions too. However, the aeronautics industry has also very high standards, multiple testing and certification steps for new technologies to be approved and eventually become commercial, particularly if these new technologies pose a threat or open vulnerabilities in the operation of an airplane. The development of this technology has great potentials but also major obstacles, including trust issues of technology selection/decision makers, etc.

The objective of the use case described in this chapter is to use artificial intelligence (AI) algorithms for the improvement of reliability, dependability and criticality of the new technology called wireless avionics intra-communications [12–19]. The improvement foreseen by the development of this use case lies in the lower layers of the communication stack, focusing also on the interaction with the internal aeronautics wireline network based on a deterministic and real time technology. The AI algorithms envisaged for WAICs aim to overcome the main degrading effects onboard an aircraft, mainly interference, fading, shadowing, metallic reflections, turbulence, etc. Several of the intended AI algorithms will use multiple antenna diversity which requires new modelling, prediction, and analysis in a different environment such as on board an operational aircraft.

Summarizing, the objectives of this use case are focused on overall improvement and development of WAICs by:

1. Improvement of reliability of WAIC to the same or similar level as the wired safety critical avionic networks of commercial aircraft.
2. Introduction of adaptive transmission to WAIC by means of artificial intelligence (AI) using spatial diversity and other signal processing algorithms for WAIC to reduce impact of potential interference, avoid jamming, increase spectral efficiency and support low latency.
3. Prediction of channel conditions in WAIC. AI will aim to predict channel conditions of an aircraft during different moments of a mission, including turbulent conditions and detecting changing patterns according to the type of aircraft and the movement of passengers inside the cabin.
4. Increase of Technology Readiness Level of WAICs by using a prototype demonstration in a representative scenario inside an aircraft.
5. Improvement of connectivity in an aircraft by employment of reconfigurable IoT antennas.
6. Increase explainability of AI decisions in the context of WAICs.

The organization of this chapter is as follows. Section 2 presents the objectives of the use case. Section 3 provide link to the building blocks of the project that are implemented in this use case. Section 4 provides a review of the state of the art. Section 5 provides the aded value of AI and IoT. Section 6 presents the scenarios of the use case, while the remaining sections present details of the different building blocks of this use case and preliminary results.

2 Use Case Objectives

This use case addresses mainly the objectives of the use of AI algorithms for the improvement of wireless infrastructure by two means: an intrinsic improvement of wireless technology, and the second way an improvement using the information transmitted by wireless technologies. The majority of the developments of this use case lie in the first class. The reason behind these objectives is that in the lower layers we find the main trust issue that currently affects WAICs to replace cable structures on board modern aircraft. The challenge is to show that WAICs are trustworthy for critical industrial applications in this domain. The developments also cover the issue to increase dependability and match the real-time behaviour of the critical internal aeronautical networks of operational aircraft. This means to make wireless avionics links as wireline-like as possible to reduce the mismatch between the two types of networks. This implies to minimize to a great extent the issues of interference, fading, shadowing, multi-path degradation, etc.

3 Link Between Scenarios and Building Blocks

The use case of AI for WAICs is constructed on a set of technical building blocks developed by different partners and which are integrated in the final use case demonstration. The philosophy of the project InSecTT lies on the concept of cross-domain reusability of building blocks. This means that many of the building blocks that constitute this use case can be reused in other use cases or applications with convenient adaptations. The mapping of building blocks to the scenarios of this use case is given in Table 1.

4 State of the Art

A WAIC system can be defined as a wireless transmission system where the network devices or nodes are located in the same aircraft [20]. Note that this definition explicitly excludes aircraft-to-ground or aircraft-to-aircraft communications. However, these systems must not be ignored in the design of a WAIC network, as interference can arise if contiguous/similar frequency bands are used, and also because some WAICs applications must interact with these other systems. A WAIC system can thus have very diverse purposes, such as [21]: wireless sensing [22, 23], cable replacement [24], structural health monitoring [25–27], remote control and maintenance [28], object identification [29, 30], fuel tank level monitoring [23], actuation (flaps), surveying, and avionics bus communications [31–33], etc.

Note that the term WAIC also applies to other types of aircraft such as smaller or larger aircraft, helicopters [34], aerial drones, etc. A good WAIC design must consider the optimum number and location of nodes, access points, or signal repeaters/relays, which ensure appropriate coverage where service is to be provided.

The design of a WAIC system must consider its integration into the existing communication infrastructure on aircraft. Avionics Full-Duplex Switched Ethernet (AFDX) is a data network for safety-critical applications that uses dedicated band-

Table 1 InSecTT sub-building blocks mapping for WAICS use case

TBB	Scenario 1	Scenario 2	Scenario 3
TB2.1			AI for multi-parameter sensing
TB2.2	AI for interference detection, mitigation, channel est., equalization, and prediction Interference detection and mitigation	AI model implementation and validation Multiple metrics assessment	AI for optimized sensing across aircraft
TB2.3			Sensor dynamics model
TB2.4	Metrics for V&V of AI tools for wireless systems	Metrics for V&V tools for wireless systems. Test generation, jamming attacks generation. Explainability of digital signal classification by an AI neural network	AI for multi-parameter sensing
TB2.5	Trustworthiness metrics for WAICs architectures	Trustworthiness metrics for WAICs architectures	
TB3.2	MIMO modelling, interference and propagation modelling	AI for interference detection, suppression channel estimation equalization and conflict resolution	AI for sensor management
TB3.4	Latency evaluation WAICs	Latency evaluation WAICs	
TB3.5	Security testing System level simulation. Multiple approach	Security testing System level simulation. Multiple approach	Security testing System level simulation. Multiple approach

width while providing deterministic Quality of Service (QoS) [35]. AFDX is based on IEEE 802.3 [36] Ethernet technology. Other bus technologies in aeronautics are CAN (Controller-Area-Network) [37], TTP (Time Triggered Protocol) and wavelength division multiplexing over optical fibre. The work in [31, 32] proposed a hybrid network based on the standard 802.11e (which is the flavour of WiFi technology with support for QoS) with the internal AFDX Ethernet network which is standard in modern passenger aircraft.

Standardization for WAICs has been materialized over the last few years. The initial ITU recommendation in [21] provided definitions and service desice recommendations in the ISM free frequency bands. However, subsequent recommendations and standardization have defined a specific band allocation and more details of physical layer design [12–18]. This PHY-layer of WAICs is particularly challenging because the physical configuration of an aircraft changes depending on the aircraft model and manufacturer. Outside the aircraft, wireless transmissions can suffer from reflections from the fuselage or moving metallic parts. While the aircraft is flying,

Table 2 WAICs scenario 1

Use case	AI-enriched wireless avionics resource management and secure/safe operation
Scenario	Interference detection and cancellation
Description	Use of signal processing tools for multiple antennas to detect intentional and non-intentional jamming interference on board aircraft that may harm operation of the emerging WAICs technology mitigation, channel est., & and validation across aircraft
Trigger	Designer of WAIC system running the test scenario
Flow of events	Flow 1. Entity model implemented in a given context with distances and obstacles, attackers, relevant to propagation and performance of the network 2. Propagation and interference models used to calculate link layer metrics 3. Link layer metrics are modified to account for advanced PHY layer and also to feed AI algorithms. Attacks are also actively generated 4. Decision on resource allocation and interference mitigation based on MIMO and other like adaptivity measures is implemented 5. Metrics of performance are collected over a number of simulation or demonstrator runs also feeding learning algorithms that will reuse the results in future runs Normal flow 1. Sensors nodes in the cabin of the aircraft send measured data via wireless network 2. Gateway nodes receive data and measure signals parameters 3. Direction of arrival of the signal and possible spatial information are calculated by the system Exceptional flow 1. Sensors nodes in the cabin of the aircraft send measured data via wireless networks and obstacles, attackers, relevant to propagation and performance of the network 2. A jamming signal is introduced in the cabin 3. Gateways try to receive data from sensors. Jamming signal is detected (but not yet classified) and measured 4. Direction of arrival of the signal and possible spatial information are calculated by the system 5. Alert is raised, as the system detects an interference anomaly
Input data	Physical layer multiple distributed antennas across the aircraftq
Output data	Identification of angle of arrival (AoA) of potential interferer or MIMO subspace definition. Interference compensation MIMO subspace or beamforming arrays that minimize distortion metrics
Infrastructure	PHY-layer simulation, system-level simulation and validation tools
TBB	BB2.2, BB3.2, BB3.4, BB3.5

Table 3 Scenario 2

Use case	AI-enriched wireless avionics resource management and secure/safe operation
Scenario	Verification and validation of WAICs
Actors	Transmitters, receivers and jammers in wireless communication, testing framework and the designer of WAIC system
Description	The goal of this scenario is to create a wireless testing framework capable of: Simulating wireless communication channel Simulating additional interferences (both intentional and unintentional) in the channel Applying real measured signals to the simulation Applying a real measured channel to the simulation Connecting real nodes to the simulated channel/interferences Handling multiple by standing devices in the simulation Overall, the framework should be able to simulate possible real-life situations, with capability to connect actual hardware mounted in avionics systems
Trigger	Designer of WAIC system running the test scenario
Flow of events	Flow 1. The WAIC system designer creates a test scenario 2. The WAIC system designer runs the test scenario 3. Channel is created, transmitter, receiver and jamming device are connect to the framework 4. Measurements are running 5. Test results are presented on UI
Input data	Signals from transmitter, signals from jammer, channel configuration
Output data	Measurements of received signal
Infrastructure	Depending on the scenario: receiver, transmitter, jammer, testing framework deployed on a server or a cloud
TBB	TBB 3.5: Verification, validation, accountability

turbulence conditions, high altitude, extreme temperature, vibration, etc. might also change propagation conditions. Inside aircraft, there are several challenges too. For example, passengers and crew moving constantly around cockpit and bays can modify propagation conditions; luggage with different materials could cause absorption or further reflection; windows can be transparent to radiation, thus being a source radiation loss and interference to outside networks or other planes; inside the aircraft radiation can cause interference to navigation and critical aircraft systems, etc. Multipath propagation is likely to be increased too, mainly due to reflections on metals or signals travelling through different materials. Interference between contiguous systems can also be an issue in the future of WAICs.

The works in [38, 39] propose an electromagnetic modelling of cabins for WiFi, UMTS and Bluetooth technologies. The European project WirelessCabin [40–43] has addressed the measurement and propagation modelling of aircraft focusing on

Table 4 Scenario 3

Use case	AI-enriched wireless avionics resource management and secure/safe operation
Scenario	Devices, sensors inside the aircraft and sensors outside
Description	Building the devices that can harvest energy and also sense some information from passengers/systems Example, wind speed, push of a button, etc.
Trigger	The change in physical parameters
Flow of events	Flow 1. Design of devices 2. Testing them for the availability of energy 3. Increasing the reliability
Input data	Physical layer multiple distributed antennas across the aircraft
Output data	Identification of physical parameters or user driven information Wind speed information
Infrastructure	Embedded System/device
TBB	BB2.1 BB2.3 BB2.2, BB3.2

path-loss modelling, multi-path delay profile characterization, and frequency selectiveness. The work in [44] provided an electromagnetic propagation study based on FDTD (Finite-Difference Time-Domain) for the optimization of the number and location of access points inside the cabin of an aircraft. Multiple works exist on channel modelling for aircraft, inside the cabin our outside the cabin, or targetting interference to internal instruments and/or targetting the effects of passengers or multiple materials on propagation factors.

Testing of existing standards such as ZibBee, IEEE802-25-4 in all the different flavours, have been presented in different works, measuring different aspects from reliability, latency, emissions, and robustness to attacks (Security). The authors in [45] provide an extensive analysis of different types of security attacks using an adversary model, where the adversary can be internal or external and the attack can be passive or active. Security features of COTS technologies for wireless avionics have been also addressed in [46]. Other security and privacy considerations for wireless avionics communications can be found in [45, 47–49].

5 AI/IoT Added Value

AI is expected to bring several benefits to WAICS technology. In particular, the learning phases provided by AI can help us use data sets from different scenarios to refine the processing of signals in future or in current instances of the scenarios. For example, for interference, it can help us identify clearly multiple spatial signatures that match previous issues or events included in our data sets. AI can be applied in this use-case at various points:

1. To improve early recognition of digital signals
2. To improve antenna beam-forming

In the context of avionics, AI will be mostly deployed to assist in solving complex RF transmission problems, where the application of AI will result in a better overall outcome (e.g. use of the frequency spectrum, cope with electronic RF disturbances) as traditional algorithms will. Due to the complexity of the problems addressed, clarification of the AI decision/classification process is desired by the experts using the system. Within the scenarios, various attempts shall be made to visualize the AI classification decisions for system experts. AI will be used to improve the reliability, latency and criticality (real-time support) of the wireless avionics' layers. The aim is to make the wireless links onboard the aircraft as wireline-like as possible in terms of performance. This is, the wireless network is expected to behave like the internal wireline network of the aircraft which is a real time technology. More specifically, the real time virtual links of the aeronautical bus standards are expected to be mapped transparently into the wireless side of the network. This involves a huge improvement in reliability and real time performance. AI is expected to help WAICs achieve this challenging ambition.

6 Scenarios

This section deals with the scenarios proposed by this use case to provide an instance example of how AI will improve the operation of WAICs.

6.1 Scenario 1: Interference Detection and Cancellation

One of the most challenging aspects of the technology WAICs to be highly reliable and trustable is the relatively small area of deployment and the complexity/density of all critical subsystems of an operational aircraft. This can be worsened by the highly unpredictable propagation channels and the extreme environmental conditions that can be found at different moments of a flight mission: take-off, taxi, landing, etc. Perhaps the most important issue on board an aircraft is the potential interference towards the WAICs network (coming from different directions internal or external to the aircraft) or the interference from the WAICs system to other on-board equipment. This scenario is focused on the modelling, measurement, detection and rejection/compensation of several sources of non-intentional or intentional (Jamming) interference on board the aircraft considering different positions of the interfering nodes or different strategies of the jamming attackers (see Fig. 1). Artificial intelligence tools will be designed to improve all the detection and compensation

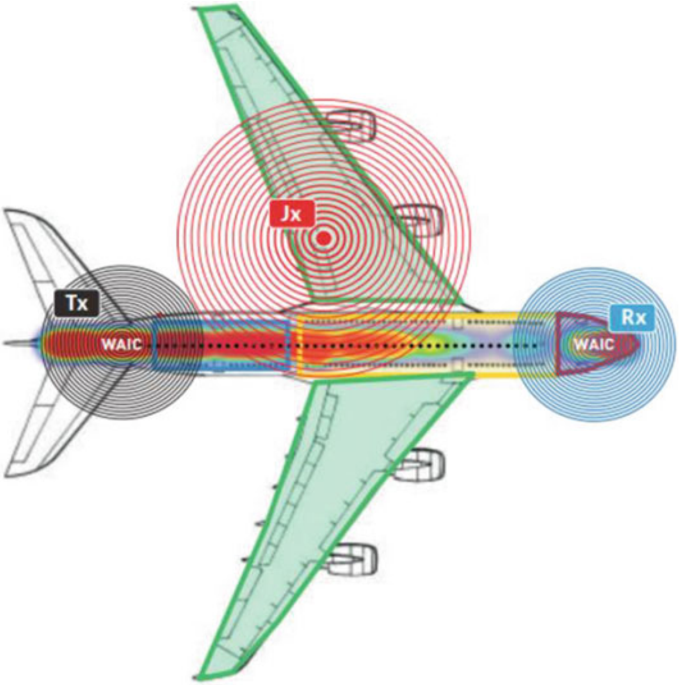

Fig. 1 Interference characterization for WAICs using AI

mechanisms and thus boost the reliability of WAICs systems under different aircraft conditions. More details of scenario 1 can be found in Table 2.

6.2 Scenario 2: Verification and Validation of WAICs

As wireless communication starts playing an important role in avionic intra-communication, a reliable testing environment becomes a necessity. The main objective of this scenario is to provide a framework for verification and validation of WAICs (Table 3).

6.3 Scenario 3: Battery-Less Devices

There is a need to reduce the wires and collect input/context information inside and outside of the aircraft. An initial passive switch developed in the project SCOTT is improved here in InSecTT to optimize communication performance, extend battery

Fig. 2 Example of a passive switches application

life and reduce interference on board aircraft (see Fig. 2). More details of scenario 3 are given in Table 3. The passive switch consists of a piezoelectric material that can produce a pulse of electromagnetic energy with a single deformation or pressing the switch by hand. This provides formidable communication capabilities without any battery support or extended battery life.

7 Performance Evaluation

This Section presents the details of the evaluation of some aspects of the scenarios described in previous sections. The core of the performance evaluation verification and validation of WAICs in this use case is the development of a system level simulator that contains all the details of synthetic and realistic data sets for channel power and interference location.

The process of verification, validation is conducted using a system level evaluation tool with an architecture shown in Fig. 3. The system level simulation can be defined as the detailed accurate representation of the environment where the system will operate. The simulation must include all the relevant processes either deterministic or random that play role in the performance on the system. In a wireless network, the channel model is a crucial component to recreate the environment where signals will propagate. In our case, the system level simulator considers a realistic virtual model of an aircraft and a synthetic channel geometry-base stochastic model. The details of the physical layer processes to be included in the system level simulator depends on the target and objective of the simulation. In our case, we intend to evaluate if wireless transmission assisted by artificial intelligence is viable up to the high standards of the industry in a difficult environment such as an operational aircraft (See symbol error rate performance results in Fig. 4).

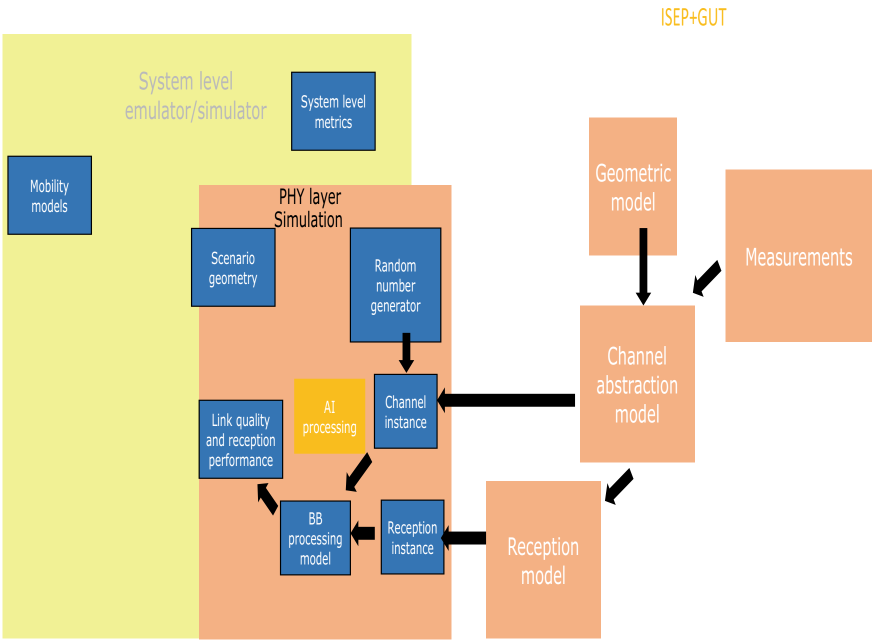

Fig. 3 Architecture of the system level simulation tool for the process of verification and validation of WAICs

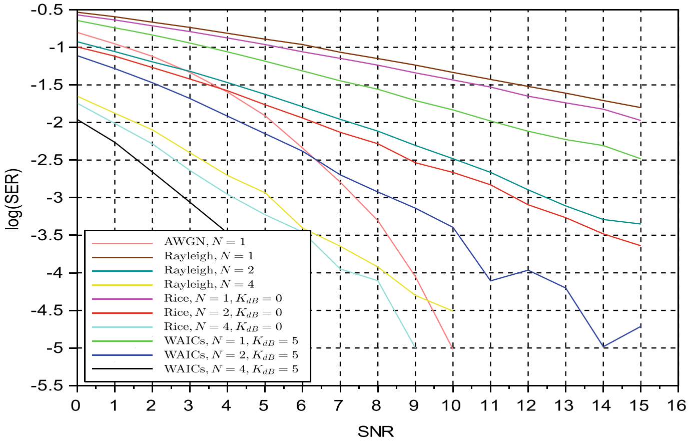

Fig. 4 SER (Symbol Error Rate) for different wireless links with different numbers of antennas N

7.1 *Propagation Channel Modelling*

A detailed channel model with multiple ray tracing and stochastic scatterers has been proposed for aircraft propagation (Table 4). The main idea is to calculate the

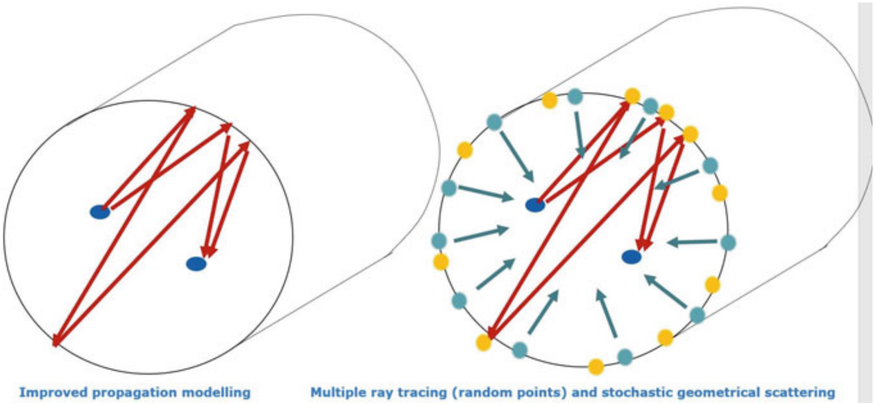

Fig. 5 Cylinder geometry for in-cabin channel modelling

reflections (deterministic) of multiple orders that occur inside a hollow structure of the aircraft. Different models have been used including a simple cylinder, followed by a cylinder and a solid floor inside as shown in Fig. 5. The channel model has also evolved to considered seats and passengers inside the aircraft (see Fig. 6). More recently, the channel model has considered two different profiles revolving around the central axes that define both the transversal section of the aircraft and its variations along the length of the aircraft (see Fig. 7). This modification allows us to consider any type of aircraft model and obtain a realistic virtual model of the internal mechanical parts of the aircraft.

Additionally, to address the evaluation of the coupling between internal and external networks, the channel models allows us to calculate the distribution over the windows of the aircraft. The electric fields can thus be used to calculate the radiation towards different directions in the external side of the aircraft, including the wings.

7.2 MIMO in Aeronauics

The implementation of MIMO in aeronautic commercial networks is in its infancy. For purposes of system level simulation the antenna elements will be considered as closely located and with the same set of scatterers impinging a random signal over the arrays. This leads to a natural correlation between the elements. However, our system level simulator has the option to consider additional electromagnetic coupling that naturally arises between radiating or passive elements located at close distances.

The simulator has the option to consider different processing schemes for MIMO, also enabled by AI. The advantage of MIMO is that due to spatial diversity, solutions

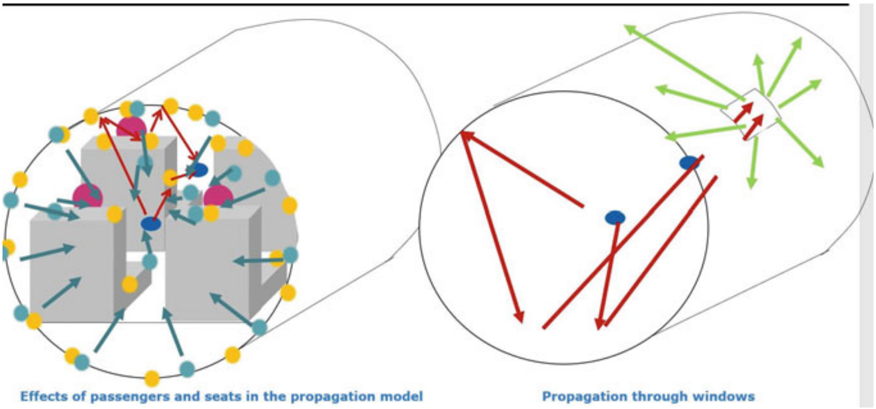

Fig. 6 Cylinder geometry for channel modelling including seats, passengers and radiation through windows

Fig. 7 Example of a aircraft profile for channel modelling

such as beam-forming and multiple antenna combining or precoding can help to reduce interference and fading, common issues in wireless networks.

The simulator has included MIMO beam-forming and direction of arrival estimation based on AI algorithms. The use of these two components is crucial to detect, track and counteract sources of jamming interference wither on board or outside the aircraft.

7.3 *Wireless Measurements*

A number of measurement campaigns of signal propagating inside a real aircraft cockpit have been conducted. The measurements consider positions of sensors across different locations of the aircraft as shown in Fig. 8. These measurements create a realistic data set to be used by AI algorithms. However, the data set does not cover all the potential positions and effects inside the aircraft. These measurements are therefore incorporated into the synthetic channel model presented in previous subsections. The parameters of the synthetic model such as Rice factor, profile decay factor, and multi-path distribution are adjusted according to the available measurements.

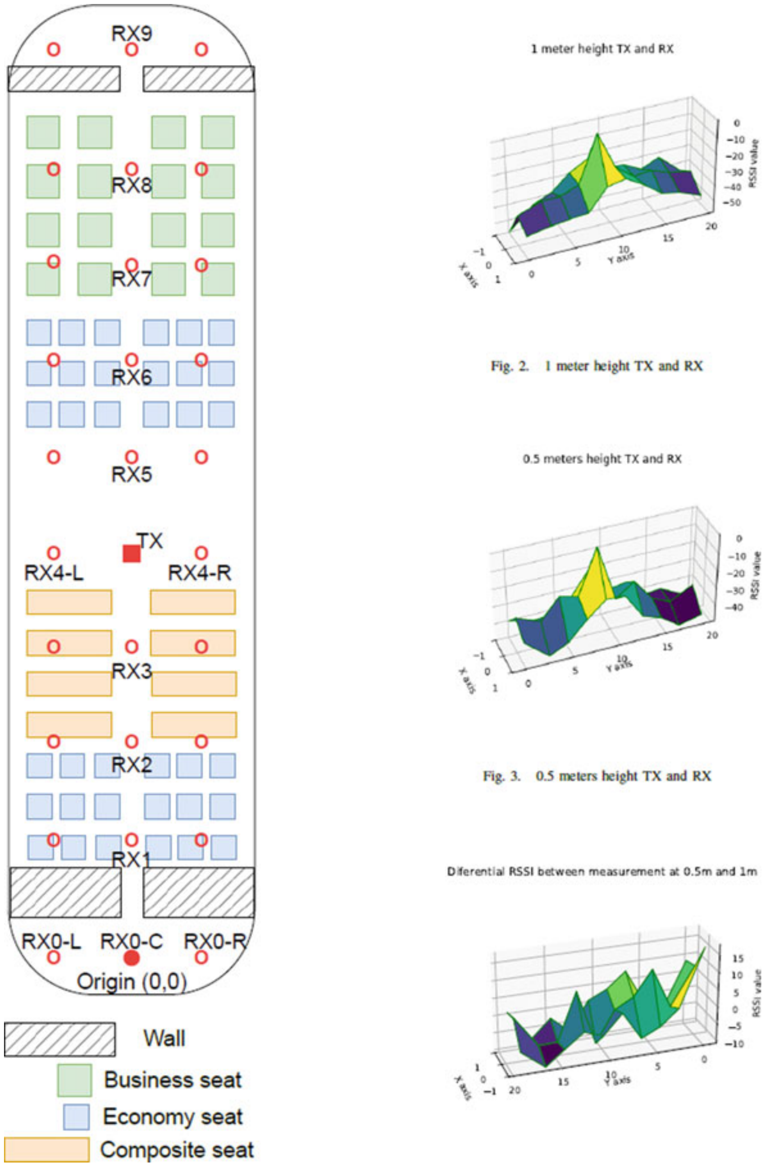

Fig. 8 Results of measurements campaign inside a Boeing aircraft

7.4 Single and Multiple Link Results

We consider a single wire-line link modelled as a channel with additive White Gaussian noise whose performance depends exclusively on the signal-to-noise ratio (SNR). The performance symbol error rate of a BPSK modulation is well known in the literature and shown in Fig. 4.

When a wireless channel model based on Rayleigh distribution is used, the performance is considerably degraded compared to the AWGN or cable performance. This is one of the main reasons behind the lack of reliability of wireless links compared to wire-line solutions.

The results using MIMO with different numbers of antennas, denoted by N show how the spatial diversity helps in reducing the effects of fading channels and get close to the performance of a wire-line system, which in this case is represented by the AWGN solution. The results have considered also different values of the Rice factor, and also the channel model proposed in previous subsections, which is labelled as "WAICS".

7.5 Active Flow Control Simulation with Jamming Interference and Node Misbehaviour

To test the operation of WAICs, we use the example of an active flow control (AFC) system enabled by a dense network of sensors and actuators over the wings of the airplane (see Fig. 9). The objective is to track the formation of the turbulent flows or the boundary layer transition between laminar and turbulent flows. This tracking needs to be in real time and with low latency to be able to enable the model of the actuation that have some known consequences on delaying the transition from laminar to turbulent flow. The performance of this system is directly related to how accurate the central computer on board the aircraft has a real time perspective of the turbulent layer transition. Delays in the network as well as attacks, and other impairments such as fading and multi path considering the channel models previously studied have been considered. The results in Fig. 10 show that when machine learning is used to predict the boundary transition layer and to detect potential interference attacks or deep fades of the communication channel, it is possible to track with less errors and in real time the boundary transition layer, which in the end would make the system more efficient. Each figure shows on the right hand side two curves, one that belongs to the real-time boundary layer, and the other curve is the curve as received by the central server. The second curve is prone to transmission errors due to fading, jamming attacks, or node misbehaviour. ML prediction helps detect parts of the curve where an error potentially occurred and therefore there is a need to compensate with a predicted value based on a training model previously calculated over similar turbulence and network conditions. All the results have been calculated using the channel models previously described over a hypothetical WAICs network

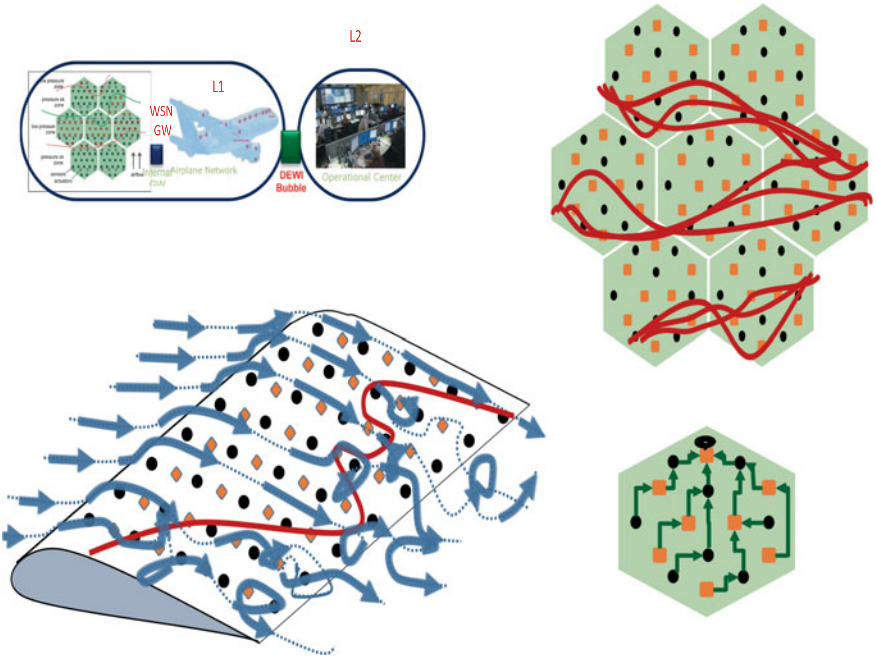

Fig. 9 Concept of active flow control using WAICs

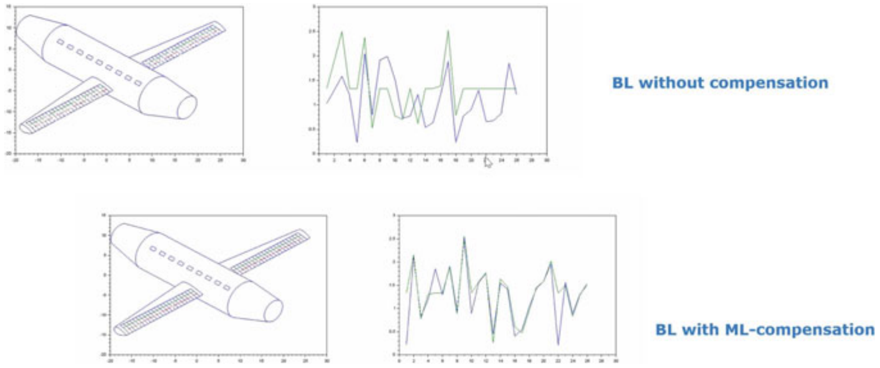

Fig. 10 System level simulation results for AFC system turbulence boundary layer tracking

operating in the 6 GHz band with 100 MHz of bandwidth and a power budget optimized to allow communication in free space loss over the surface of the wings of the mechanical model of the aircraft. The turbulence model used was proposed in the project SCOTT and consists of a space-time stochastic circular complex Gaussian model with a variable mean according to the aerodynamic parameters such as vehicle speed and angle of attack.

8 Conclusions

The results of our modelling of the Physical layer of wireless avionics intra-communication assisted by AI point towards several interesting conclusions. The use of MIMO can quickly reach an optimum point where wireless links behave as wire-line links. However, when interference is considered the demands can grow rapidly. The use of AI becomes fundamental in avionics scenarios with higher level of scattering distribution, and mainly to provide real-time capabilities for critical applications. We have shown that for an application of active flow control, the use of machine learning can compensate multiple errors in the tracking of a metric that measures the formation of turbulence over the wings of an aircraft. The errors are caused by a combination of fading, jamming interference and node misbehavior or node functional faults. A negative aspect of AI that was found in this work was the complexity of the algorithms that could have an impact on delay sensitive applications.

References

1. Kumar, M.: “Wireless Versus Wireline” Competing Broadband Access Technologies, 1 Sept. 2012. SSRN: http://ssrn.com/abstract=2305028 or http://dx.doi.org/10.2139/ssrn.2305028
2. Liu, J., Demirkiran, I., Yang, T., Helfrick, A.: Communication schemes for aerospace wireless sensors. In: IEEE/AIAA 27th Digital Avionics Systems Conference, 26–30 Oct. 2008, pp. 5.D.4-1,5.D.4-9 (2008). https://doi.org/10.1109/DASC.2008.4702861
3. Long, L.N., Schweitzer, S.J.: Information and knowledge transfer through archival journals and online communities. AIAA Paper 2004-1264, Aerospace Sciences Meeting, Reno, NV (Jan. 2004)
4. Harrington, M.: Introduction to wireless systems in aerospace applications. Presentation IEEE Proceedings. http://www.ieee-stc.org/proceedings/2008/pdfs/MH1933.pdf
5. Fly-by-Wireless (FBWSS): Benefits, risks and technical challenges. CANEUS Fly-by-Wireless Workshop, Orono, ME, USA 08/24/2010. Dipl.-Ing. Oroitz Elgezabal, German Aerospace Center (DLR), Institute of Flight Systems (2010)
6. Field, S., Arnason, P., Furse, C.: Smart wire technology for aircraft applications. In: Proceedings of the 5th Joint NASA/FAA/DoD Conference on Aging Aircraft, Orlando, FL (Sept 2001)
7. Dornheim, M.A.: New rules and hardware for wiring soon to emerge. In: The Aviation Week Space Technology, vol. 2 (Apr. 2001)
8. Stone, T., Alena, R., Baldwin, J., Wilson, P.: A viable COTS based wireless architecture for spacecraft avionics. In: IEEE Aerospace Conference, 3–10 Mar. 2012, Big Sky MT, pp. 1–11 (2012). https://doi.org/10.1109/AERO.2012.6187104
9. Studor, G.: NASA Fly-by-Wireless Update. http://hdl.handle.net/2060/20100031691
10. Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., Cayirci, E.: Wireless sensor networks: a survey. Comput. Netw. Elsevier **38**, 393–422 (2002)
11. Rawat, P., Singh, K.D., Chaouchi, H., Bonnin, J.M.: Wireless sensor networks: a survey on recent developments and potential synergies. J. Supercomput. **68**, 1–48 (2014). https://doi.org/10.1007/s11227-013-1021-9
12. Technical characteristics and operational objectives for Wireless avionics intra-communications (WAIC) Report M. 2197 (ITU-R Report). http://www.itu.int/pub/R-REP-M.2197

13. Technical characteristics and protection criteria for Wireless Avionics Intra-Communication systems, Recommendation ITU-R M.2067, approved Nov. 2014. http://www.itu.int/rec/R-REC-M/recommendation.asp?lang=en&parent=R-REC-M.2067
14. Technical conditions for the use of the aeronautical mobile (R) service in the frequency band 4 200- 4 400 MHz to support wireless avionics intra-communication systems, Report ITU-R M.2283, approved July 2015. http://www.itu.int/rec/R-REC-M/recommendation.asp?lang=en&parent=R-REC-M.2085
15. Technical characteristics and spectrum requirements of Wireless Avionics Intra-Communications systems to support their safe operation, Report ITU-R M.2283, approved Dec. 2013. http://www.itu.int/pub/R-REP-M/publications.aspx?lang=en&parent=R-REP-M.2283
16. Technical conditions for the use of the aeronautical mobile (R) service in the frequency band 4 200-4 400 MHz to support wireless avionics intra-communication systems, Report ITU-R M.2283, approved July 2015. http://www.itu.int/rec/R-REC-M/recommendation.asp?lang=en&parent=R-REC-M.2085
17. Technical characteristics and spectrum requirements of Wireless Avionics Intra-Communications systems to support their safe operation, Report ITU-R M.2283, approved Dec. 2013. http://www.itu.int/pub/R-REP-M/publications.aspx?lang=en&parent=R-REP-M.2283
18. Consideration of the aeronautical mobile (route), aeronautical mobile, and aeronautical radio navigation services allocations to accommodate wireless avionics intra-communication, Report ITU-R M.2318, approved Nov. 2014. http://www.itu.int/pub/R-REP-M/publications.aspx?lang=en&parent=R-REP-M.2318
19. Compatibility analysis between wireless avionics intra-communication systems and systems in the existing services in the frequency band 4 200-4 400 MHz, Report ITU-R M.2319, approved Nov. 2014. http://www.itu.int/pub/R-REP-M/publications.aspx?lang=en&parent=R-REP-M.2319
20. Robles, R., Tovar, E., Cintra, J., Rocha, A.: Wireless avionics intra-communications: current trends and design issues. In: International Conference on Digital Information Management (ICDIM 2016). 19–21 Sept. 2016. Porto, Portugal (2016)
21. ITU Preliminary Document 5B/167-E, Characteristics of WAIC systems and bandwidth requirements to support their safe operation
22. Wilson, W., Atkinson, G.: Wireless sensing opportunities for aerospace applications. Sens. Transducers J. **94**(7), 83–90 (2008)
23. Goldsmith, D., Gaura, E., Brusey, J. et al.: Wireless sensor networks for aerospace applications-thermal monitoring for a gas turbine engine. In: Proceedings of Nanotech Conference and Expo, pp. 507–512. CRC Press-Taylor & Francis Group, Boca Raton, FL (2009)
24. Collins, J.: The challenges facing U.S. navy aircraft electrical wiring systems. In: Proceedings of the 9th Annual Aging Aircraft Conference (2006)
25. Haowei, B., Atiquzzaman, M., Lilja, D.: Wireless sensor network for aircraft health monitoring. In: Proceedings of the First International Conference on Broadband Networks, 2004. BroadNets 2004. pp. 748, 750 (25–29 Oct. 2004)
26. Yedavalli, R.K., Belapurkar, R.K.: Application of wireless sensor networks to aircraft control and health management systems. J. Control Theory Appl. **9**(1), 28–36 (2011)
27. Bai, H., Atiquzzaman, M., Lilja, D.: Wireless sensor network for aircraft health monitoring. In: Proceedings of the 1st International Conference on Broadband Networks. IEEE Computer Society, pp. 748–750. Los Alamitos, CA (2004)
28. Hamman, R.: Wireless solutions for aircraft condition based maintenance systems. In: IEEE Aerospace Conference Proceedings, 2002, vol. 6, pp. 6-2877, 6-2886 (2002)
29. Floerkemeier, C., Sarma, S.: An overview of RFID system interfaces and reader protocols. In: IEEE International Conference on RFID 2008, pp. 232, 240 (16–17 Apr. 2008)
30. Falk, R., Kohlmayer, F., Kopf, A., Mingyan, L.: High-assurance avionics multi-domain RFID processing system. In: IEEE International Conference on RFID, pp. 43, 50 (16–17 Apr. 2008). https://doi.org/10.1109/RFID.2008.451936

31. Sambou, B., Peyrard, F., Fraboul, C.: Scheduling avionics flows on an IEEE 802.11e HCCA and AFDX hybrid network. IEEE Symposium on Computers and Communications (ISCC), pp. 205, 212 (28 June 2011–1 July 2011). https://doi.org/10.1109/ISCC.2011.598384
32. Sambou, B., Peyrard, F., Fraboul, C.: AFDX wireless scheduler and free bandwidth managing in 802.11e(HCCA)/AFDX network. In: 7th International Wireless Communications and Mobile Computing Conference (IWCMC), 2011, pp. 2109–2114, (4–8 July 2011). https://doi.org/10.1109/IWCMC.2011.5982860
33. Zhang, C., Xiao, J., Zhao, L.: Wireless asynchronous transfer mode based fly-by-wireless avionics network. In: IEEE/AIAA 32nd Digital Avionics Systems Conference (DASC), pp. 4C5-1, 4C5-9, (5–10 Oct. 2013). https://doi.org/10.1109/DASC.2013.6712589
34. Ketcham, R., Frolik, J., Covell, J.: Propagation measurement and statistical modeling for wireless sensor systems aboard helicopters. IEEE Trans. Aerosp. Electron. Syst. **44**(4), 1609–1615 (2008)
35. ARINC664 INC. Aeronautical Radio. ARINC Specification 664. Avionics Full-Duplex Switched Ethernet. Annapolis, Maryland: Aeronautical Radio, Inc
36. Ethernet IEEE 802.3 Standard for Information technology-Telecommunications and information exchange between systems- Local and metropolitan area networks-specific requirements Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications
37. ISOCAN ISO 11898-1:2003 Road vehicles-Controller area network (CAN)-Part 1: Data link layer and physical signalling
38. Niebla, C.P.: Topology and capacity planning for wireless heterogenous networks in aircraft cabins. In: Proceedings of PIMRC05, pp. 2088–2092 (11–14 Sept. 2005)
39. Niebla, C.P.: Coverage and capacity planning for aircraft in-cabin wireless heterogenous networks. In: Proceedings of VTC 2003, pp. 1658–1662 (6–9 Oct. 2003)
40. Leipold, F., Tassetto, D., Bovelli, S.: Wireless in-cabin communication for aircraft infrastructure. Springer US, J. Telecommun. Syst. 1–22
41. Holzbock, M., Hu, Y.F., Jahn, A., Werner, M.: Advances of aeronautical communications in the EU framework. Int. J. Satell. Commun. Netw. **22**, 113–137 (2004). https://doi.org/10.1002/sat.777
42. WirelessCabin, FP4 EU project. http://wirelesscabin.triagnosys.com/
43. Riera Diaz, N., Holzbock, M.: Aircraft cabin propagation for multimedia communication. In: Proceedings of the 5th European Workshop on Mobile/Personal SATCOMS, Baveno (Lake Maggiore), Italy (Sept 2002)
44. Chao, Z., Yu. J., Pank, K.: Multiple access points deployment optimization in cabin wireless communications. IEEE Antennas Wirel. Propag. Lett. **12**, 1220–1223 (2013)
45. Wargo,C.A., Dhas, C.: Security consideratiolis for the e-enabled aircraft. In: Proceedings 2003 IEEE Aerospace Conference, vol. 4, pp. 1533–1550 (8–15 Mar. 2003)
46. Sampigethaya, K., Poovendran, R., Bushnell, L., Mingyan, L., Robinson, R., Lintelman, S.: Secure wireless collection and distribution of commercial air-plane health data. IEEE Aerosp. Electron. Syst. Mag. **24**(7), 14 (20 July 2009). https://doi.org/10.1109/MAES.2009.5208555
47. Sampigethaya, K., Poovendran, R., Bushnell, L.: Secure operation, maintenance and control of future e-enabled airplanes. Proc. IEEE **96**(12), 1992–2007 (2008)
48. Sampigethaya, K., Poovendran, R.: Privacy of air traffic management broadcasts. IEEE Digital Avionics
49. Cramer, J.: Update on WRC-12 issues impacting wireless avionics intracommunications. ITU-R Working Party 5B and Future Regulatory Considerations (Sept 2010)