Wireless Connectivity in Airplanes: Challenges and the Case for UWB

JORGE F. SCHMIDT1,2, DANIEL NEUHOLD2, CHRISTIAN BETTSTETTER1,2, (Senior Member, IEEE), JIRKA KLAUE3, AND DOMINIC SCHUPKE4, (Senior Member, IEEE)

1Lakeside Labs GmbH, 9020 Klagenfurt, Austria
2Institute of Networked and Embedded Systems, University of Klagenfurt, 9020 Klagenfurt, Austria
3Airbus, 22335 Hamburg, Germany
4Airbus, Central Research and Technology, Communication Technologies, 81663 Munich, Germany

Corresponding author: Jorge F. Schmidt (schmidt@lakeside-labs.com)

This work was supported in part by the Carinthian Economic Promotion Fund [Kärntner Wirtschaftsförderungs Fonds (KWF)] under Grant 20214/26811/38805, in part by Lakeside Labs GmbH, Klagenfurt, Austria, and in part by Airbus, Munich/Hamburg, Germany.

ABSTRACT Wireless solutions for on-board communications are gaining momentum in the aerospace industry with the aim to further improve flight safety, reduce aircraft costs, and lower environmental impact. Also passenger infotainment services are increasingly realized in a wireless way and call for high-rate connectivity to the Internet. There are many issues though, including security, coexistence, and power sustainability. We argue that ultra-wideband (UWB) technology is a promising implementation path for such intra-aircraft communications. From a power sustainability perspective, UWB attains a unique trade-off between power consumption and data rate that can become a key enabler. Experimental results from a proof-of-concept deployment of off-the-shelf UWB transceivers in an Airbus A319 support our discussion and shed light on the challenges ahead.

INDEX TERMS Aeronautics, UWB, WAIC, wireless sensor networks.

I. INTRODUCTION Wireless communications plays a central role in aeronautics today, as the concept of airplanes participating as intelligent nodes in a global network of satellite, air, and ground communications gains momentum [11]–[11]. Ongoing developments address wireless connectivity taking over part of the traditional wiring between aircraft sensors and equipment and rethinking air-to-ground communications for broadband connectivity to passengers [7], [9], [11]. This momentum is supported by the allocation of an exclusive operation band for intra-aircraft communications [12] and the worldwide deployment of 5G systems fitting well to air-to-ground communications. Intra-aircraft and aircraft-to-ground communications advance simultaneously, yet their objectives are different. Whereas intra-aircraft communications targets the technological advancement of aircraft with aeronautics companies as the main players, aircraft-to-ground communications targets the improvement of passenger experience and the development of business opportunities for telecommunication operators, content providers, and airlines [7].

The associate editor coordinating the review of this manuscript and approving it for publication was Matti Hämäläinen.
a significant fraction of the weight while increasing at the same time aircraft safety. From an economic perspective, a large share of maintenance costs are associated with wire failures that are hard to isolate for repair and turn expensive because of the time the aircraft is kept from flying. Wire-related complications also concern the installation of new features and the customization of the cabin layout, which require retrofit work.

However, the use of wireless technologies inside the aircraft goes beyond its use for wire replacement. New sensing and monitoring possibilities brought by the ease of deployment of wireless on board can further reduce maintenance costs and prevent unexpected accidents. These are the long-run motivation for going wireless and have the potential of making a disruptive change in the aeronautical business. Sensor installations that are currently infeasible due to wiring restrictions can be enabled. The perspective of extensive sensing (e.g., structural or mechanical sensing) can offer another dimension to predictive maintenance, reducing costs, and allowing a better monitoring of failure sources, which is currently done by visual inspection in many cases.

There are many milestones ahead for intra-aircraft wireless communications and many challenges to solve along the way. The benefits that wireless brings are clear but so are the security concerns. Wired installations are physically non-accessible whereas wireless are by nature open. How to handle signal jamming attacks by devices on board and how to secure the wireless traffic are still issues that require answers before systems can be deployed. Also of importance is the challenge of powering the wireless network. A deployment of hundreds of sensors only makes sense if it is done in a “place and forget” manner. Power sustainability of the sensors on ambiance energy is critical for the technology success. Last but not least, new paradigms for aircraft-to-ground connectivity services also add significant coexistence constraints to the design.

This article first describes basic concepts for intra-aircraft communications and its operational framework. We then discuss the system-level requirements in terms of network performance targets and the influence of the aircraft certification process. Main challenges in terms of network security and sustainable powering of the nodes are subsequently addressed highlighting ongoing efforts and design concepts. The case of UWB as an enabling technology is subsequently addressed. First, we describe how it adapts to the system requirements, its competitive fit to the security and power challenges, and the current regulatory situation. Afterward, we present results from a proof-of-concept testbed deployed in an Airbus A319, to shed light on open questions for the next few years from a broader perspective.

### II. INTRA-AIRCRAFT COMMUNICATIONS

Intra-aircraft developments are led by the wireless avionics intra-communications (WAIC) project, an initiative bringing together major aerospace companies like Airbus, Boeing, and Embraer [9]. The project wants to solve common issues associated with wireless communication between aircraft components, covering safety and general purpose applications (see examples in Table 1 and many more in the survey [8]). The dissimilar redundancy coming from the wireless deployment enhances the robustness to mechanical failure. Although wireless links are more vulnerable to security threats, the complementary wire-wireless approach guarantees that hard-wired sensing and actuation can be used for consistency checks in detecting security attacks [13].

#### A. OPERATIONAL FRAMEWORK AND USE CASES

The ITU report M.2197 published in 2010 describes the technical features and operational objectives of WAIC systems [14]. The rewards pushing WAIC activities are primarily reliability improvements in the monitoring of moving and rotating parts with their corresponding impact on flight safety, reductions of wiring complexity and weight, and gains in installation flexibility. A key aspect is that WAIC systems comprise a closed and exclusive network of components on-board a single aircraft, independent of the particular usage scenario. We discuss current approaches to enforce such closed and exclusive nature in Section III.

Use cases for structure health monitoring are particularly appealing for a first step implementation since many account for monitoring that are not taking place today, or have very basic functionality. Such cases can best picture the benefits that wireless technologies bring to the industry [13], [15]–[18]. Typical use cases include many mechanical systems for which close monitoring can avoid malfunctioning, which might result in maintenance costs [15]. Sensing points are currently sparsely deployed, and the ease of deployment of wireless sensors promises a more accurate monitoring.

A good example of new applications emerging from the use of wireless systems is described in [1]: Wireless sensors deployed on aircraft wings are used to improve the fuel efficiency by actively reducing the aerodynamic drag. Sensors equipped with synthetic jet actuators suck or expel air on the wings as needed to reduce friction. Another use case is the localization and identification of equipment within the

| System                      | Application (safety related marked with *) | Sensors |
|-----------------------------|-------------------------------------------|---------|
| Ice protection              | High-lift system *                        | 38      |
|                            | Water lines *                             | 128     |
|                            | Floor panel heating *                     | 50      |
| System monitoring           | Smoke/fire detection *                    | 50      |
|                            | Landing gear (brakes, shock) *            | 25      |
|                            | Door hatches *                            | 50      |
|                            | Escape slides *                           | 50      |
|                            | Galleys                                   | 25      |
| Cabin monitoring            | Equipment identification (e.g., life vests) * | 1000    |
|                            | Seat status (belt, tablet, arm rest, ...) * | 800     |
|                            | Passengers localization and tracking       | 800     |
| Cabin control               | Cabin lights and signs *                   | 600     |
|                            | Ambient lighting                          | 150     |
|                            | Monuments (toilets, tanks, ...)            | 25      |
| Structure health monitoring | Door surroundings                         | 50      |
|                            | Fuselage                                  | 150     |

| TABLE 1. Current use case specifications for the intra-aircraft network of an Airbus A380 (800 seats). |
aircraft [19]. UWB has drawn great attention in recent years for accurate indoor localization. The achievable accuracy may spawn many valuable applications in the cabin. For example, proximity switches integrated in a passenger seat can detect the table position and seat belt status, to support safety procedures. The achievable localization accuracy and required number of receiving nodes depends on the localization technique, and it is expected that there will be a trade-off between accuracy, hardware complexity, and energy consumption.

B. NETWORK ARCHITECTURE
The application scope of intra-aircraft communications comprises a large set of use cases that together demand several hundreds of nodes to be deployed and operated in a single aircraft. Figure 1 introduces the required main system components to implement the communication and coordination between them from a system-level perspective. The network topology follows a linear cellular structure providing coverage along the aircraft fuselage. This structure has the advantage of naturally enabling the segmentation of the plane into cells with more and less inter-cell interference, conditioned on their physical distance. This architecture, established in the industry, facilitates a direct comparison of different technological implementation paths.

At each cell, the sensor nodes perceive the environment and broadcast the sensed information in a secure manner to their associated wireless data concentrators that are responsible for cell traffic handling. There can be several data concentrators operating only in listening mode in each cell, providing spatial diversity through alternative signal paths and improving the resilience to network jamming attacks. The concentrators forward the captured data via a wired backbone to an application server, which after checking for data integrity aggregates the collected data from all cells. The application server fuses and processes the received data according to the requirements of the various use cases. It also allows visualizing various network information through human machine interfaces such as the monitors in the cockpit or the handheld devices for the flight attendants [20].

Most networked devices are sensor nodes, as illustrated in Figure 1 for nodes deployed across seats in the cabin. This is a challenging setup because many nodes are deployed on a small volume (see Table 1) with many obstacles, like seats and luggage, surrounding them. Obstacles create a reflection-rich propagation environment, and thus shadowing plays a major role in terms of signal impairment. Besides the aircraft structure, the passengers further obstruct the wireless signals inside the cabin. The power attenuation caused by a person can range from 3 to 6 dB [20] with close-by passengers concentrating most of the impact [21], [22].

A wireless network connecting the sensor nodes must be designed with sufficient diversity to guarantee the reliability specification in terms of latency, packet loss, and security. The provision of independent diversity sources (e.g., frequency, spatial, temporal and code diversity) largely influences the dimensioning of the network and its cost [20], which we discuss in the context of UWB in Section IV.

C. AIRCRAFT CERTIFICATION
A key aspect for the success or failure of a wireless sensor network (WSN) for intra-aircraft connectivity is its overall cost. The aircraft certification process has an impact on these costs. Regulatory agencies, such as the Federal Aviation
Administration (FAA) and the European Aviation Safety Agency (EASA), set mandatory guidelines for aircraft to be considered safe and compliant with minimum performance standards (see [14] and the documents in [9]). The certification process for composing changes to an existing aircraft as either supplements or amendments involves many steps. A certificate is only granted by a regulator after the new airborne technology has proven to have no adverse impact on safety and expected operation, under both normal and failure conditions. The use of standardized devices holds paramount importance for a cost-effective implementation since the existence of an established regulatory framework allows for faster progress through certification.

Besides hardware aspects, differences exist in the certification of safety-critical and non-safety-critical applications. Safety-critical applications correspond to flight control systems that have more strict requirements in terms of performance and reliability. These requirements must be met to obtain flight certification. Therefore, a promising path towards certifying wireless intra-aircraft systems is the development, testing, and implementation of non-safety-critical applications as a first step. These face similar technological challenges as safety-critical applications, although their less-stringent certification process prompts to an earlier implementation from which insights can be gained.

III. DEVELOPMENT CHALLENGES
The fact that the intra-aircraft network is exclusive and limited to a single aircraft makes it amenable to a WSN implementation [1], [15]–[18]. Its design is driven by the highly-obstructed propagation environment and the premise that its performance needs to be at least as good as the wire counterpart. There are several design constraints that exceed the usual network performance targets of WSNs. The security against attacks to the transported data and its resilience to jamming need to be addressed. The sustainable operation of the network on ambiance harvested energy is critical for a practical solution, since a need for massive exchanges of batteries would make the design infeasible. Further constraining the design are the implications of the coexistence with other wireless devices that are massively carried in aircraft.

A. NETWORK PERFORMANCE TARGETS
The individual use cases determine the design constraints. Some selected cases are listed in Table 1 to illustrate the number of nodes involved in typical applications. The general figures of merit for a WSN to be used for aircraft are:

- **Scalability:** Some applications might contain many nodes (i.e., one to three orders of magnitude) and the WSN should have the ability to scale to these numbers. The number of nodes per unit area can also change considerably due to the requirements of the application. Irregular sensor deployments might lead to heterogeneous network densities, which need to be handled.

- **Timeliness:** In order to keep or enhance the wired marks, measurements need to be reported in real time or shortly after (i.e., strict latency target) the event is measured, because timeliness is a figure of merit that plays a fundamental role in the avionics industry.

- **Reliability:** Sensor nodes and the network should have mechanisms that ensure reliable communications (e.g., protocols to detect and correct transmission errors or avoid congestion within the network by transport control mechanisms). Ultimately, the reliability, finely differentiated according to different services, in a service-centric manner, or quantified in terms of a packet loss rate to be met.

- **Lifetime:** As a key to reduce maintenance costs, lifetime stands as a main metric and nodes should be aware of mechanisms to save energy. Both the architectural concept (e.g., selected hardware) and the communication protocol design (e.g., duty cycling) have a strong impact on the energy budget. By reducing or even omitting batteries at sensors, the maintenance costs are reduced as accessibility is no longer a concern. Furthermore, sensor nodes’ size and weight can be lowered.

B. NETWORK SECURITY
The broadcast nature of radio waves makes possible to overhear and record wireless transmissions. The rigorous investigation of the wireless vulnerabilities and the corresponding countermeasures is a sine-qua-non condition for the acceptance by the public of wireless technologies in aircraft [23]. While the tools for securing wireless networks constantly evolve, a persistent skeptical view prevents the harnessing of the safety benefits that wireless technologies can bring.

Detailed discussions on various dimensions of aircraft security can be found in [6], [13], [24], [25]. These papers give a general view on the vulnerabilities that are specific to aircraft applications and some illustrate their potential impact through use case examples [5], [13]. Significant efforts have been devoted to tackle these vulnerabilities through cryptography with contributions ranging from side by side comparisons of secure channel protocols for avionics [26] to general adversarial testing methodologies that propose a proactive approach to security to minimize the overall threats of IoT systems [27]. Furthermore, some protocols proposed shed light into practical implementation for the aeronautics [28], [29]. Despite these valuable contributions, ensuring security in a WSN through cryptography continues to be difficult due to the usually small payload messages, which lead to high overhead. This aspect as well as approaches to provide resilience against jamming by wireless devices carried onboard (for which an approach is proposed in [29]) constitute open challenges.

C. OPERATION ON AMBIANCE ENERGY
Most use cases for a wireless intra-aircraft network rely on the ability of the sensors to operate without a connection to the aircraft power supply. How to power them in an autarkic
manner remains an obstacle to overcome. In order to attain the envisioned weight and cost cuts (maintenance plus installation), most of the deployed sensors must be able to operate on harvested energy during the entire aircraft lifespan. Design principles and hands-on experience on this topic can be found in [30] and [16].

Substantial progress was made over the last years towards energy autonomy of intra-aircraft WSNs. Given the particularities of the aircraft environment, thermoelectric harvesters are posed as a promising solution given their mature technology, the lack of moving parts, and their large commercial offer [31]. Other energy sources like vibration [17] and aircraft-specific sources [32]–[36] are considered as well in addition to mixed schemes [37] and multiple source harvesting [38]. In particular, a generalization of the multisource concept [38] to other energy sources has the potential to completely remove batteries.

The use of multicarrier based technologies for implementing wireless intra-aircraft networks has also attracted significant attention (see [8] and reference therein). We argue that current energy harvesting techniques cannot power sensors based on these technologies. While some use cases can be more fitting to the spectral efficiency of multicarrier systems, as this paper focuses on use cases operating on ambiance energy, those use cases are not discussed here.

D. COEXISTENCE WITH OTHER SYSTEMS

ITU report M.2197 draws a clear line separating intra-aircraft from aircraft-to-ground systems. Probably the most significant difference is that intra-aircraft systems are not intended for passengers’ use or in-flight entertainment. To cover these applications, the Seamless Air Alliance [7] initiative was launched in early 2018 by a heterogeneous group (Airbus, Delta, OneWeb, Sprint, and Airtel). Their aim is to design solutions to provide passengers with the high rate and low latency typically experienced on the ground.

In terms of spectrum, the WAIC project obtained in 2015 a worldwide radio frequency spectrum allocation spanning from 4.2 to 4.4 GHz, which enables the technical harmonization of equipment across regions and countries [12]. A recent study demonstrated that UWB nodes, which transmit signals filtered by a WAIC bandpass, can be used for low-rate data communication [39].

In contrast to this, the picture at the aircraft-to-ground side is not harmonized. Some airlines offer in-cabin Wi-Fi services (operating on the ISM bands at 2.4 and 5 GHz) via satellite links. Mobile network operators are also interested in a share of the market represented by continental flights that can benefit from terrestrial networks to provide in-flight connectivity. For example, Gogo deployed over 200 ground stations across the USA and Canada, and Deutsche Telekom and Inmarsat are deploying 200 ground stations in Europe to support aircraft-to-ground-communications [4].

Beyond these solutions, there are more ambitious long-term plans of mobile network operators concerning how to serve billions of passengers per year. The density of potential users inside an aircraft requires several Gbps capacity per aircraft assuming 20% of passengers demand broadband services [4]. The evolution of cellular networks is considered capable of sustaining the required rates and thus will certainly play a role in future developments. Nonetheless, many challenges to be overcome increase the uncertainty on the spectrum utilization of aircraft-to-ground systems. It cannot be discarded that, to a certain extent, network slicing techniques will enable routing some of the intra-aircraft traffic (for non-critical applications such as cargo monitoring) through the aircraft’s 5G network [4]. However, while being an interesting connecting point between aircraft-to-ground and intra-aircraft systems, it implies usage costs for the aircraft. In principle, ISM bands can also be used for intra-aircraft communications, and sensor network technologies exist operating in these bands [8]. However, many communication technologies carried by most passengers — such as Wi-Fi and Bluetooth — also operate in these bands, which makes their use less promising from the interference management and security perspectives.

Technologies outside of the crowded ISM bands providing enough throughput include UWB and sub-GHz Wi-Fi [40], [41]. However, the lack of frequency harmonization makes global use of sub-GHz Wi-Fi for aircraft complex. UWB appears to have the potential to provide a cost-effective solution for supporting intra-aircraft communications. The UWB standard IEEE 802.15.4 from 2011 considers several operation bands. One of them is particularly fitting since it overlaps with the band allocated to WAIC systems [42]. Figure 2 shows the spectrum allocation for the frequency range of interest. It demonstrates how the UWB transmission of an off-the-shelf, standard-compliant transceiver (using band 3) overlaps with the WAIC band, meeting the transmission mask defined in [12], and without introducing significant interference to neither currently-allocated LTE bands (over different geographical regions) nor ISM bands. The use of UWB in the depicted channel significantly simplifies interference management. Interference will not come from a variety of on-board deployed wireless systems but rather only from UWB devices and possibly from the radio altimeter (allocated in the WAIC band) which was found to be not harmful [43].

IV. THE CASE FOR ULTRA-WIDEBAND AS AN ENABLING TECHNOLOGY

The technological choice to support intra-aircraft systems is highly constrained by its coexistence with aircraft-to-ground systems and largely restricts its operation band. The certification process further reduces the set of possible implementation technologies to the standardized ones to ease the certification. On top of this, long-term goals for the network functionality call for a technology that is capable of delivering high network throughput. UWB technology gathers a quite particular set of features, which designates it as a well-fitting candidate in this complex context.

The use of UWB for intra-spacecraft communications is an active research area where a set of relevant results, ranging
The coexistence of UWB with other wireless technologies is an active research field. A theoretical framework concerning how UWB and narrowband systems [51] outlines the conditions under which interference from UWB to narrowband systems can be approximated as Gaussian noise: Such approximation is accurate if the narrowband link experiences Rayleigh fading, or if several UWB pulses are received within each narrowband symbol. The Rayleigh assumption is reasonable for in-cabin propagation, and the pulse duration assumption holds for the timing of the relevant technologies (mainly LTE, Wi-Fi, and Bluetooth). Other studies like [52] focus on system-specific coexistence, where the impact of the cumulative interference from multiple UWB systems to the downlink of GSM and CDMA systems is discussed. Acceptable density bounds for UWB devices are derived that guarantee reasonable performance of the coexisting systems. Results on the coexistence of Wi-Fi systems with UWB are available in [53] and [54], where the latter presents theoretical emission limits for UWB devices interfering an IEEE 802.11n network.

Considering the ongoing research, and with short to midterm developments in mind, channel 3 from the UWB standard (shown in Figure 2) is a fitting candidate in terms of coexistence. It does not overlap with current ISM and mobile networks. The WAIC band is only allowed for intra-aircraft communication, respecting interference to radio altimeters in this band [43], [55]. Nevertheless, the required restrictions to the transmit power of devices operating in the WAIC band are met by the current UWB specification and might contribute to lifting the UWB restrictions for aircraft use. Additionally, UWB can be used for inter-aircraft communication. Further studies are needed to fully determine the impact of the UWB node density envisioned for aircraft applications. The risk of excessive interference can be reduced if orthogonal multiple access techniques are employed, but this is yet to be confirmed. Such an orthogonal access control is not a compromise solution since it is commonly used as a means to reduce the energy consumption at nodes. A lift of the UWB restrictions in some countries may be granted by regulators, arguing on the benefits of UWB (as done in this article).

Coexistence results so far suggest that other channels defined in the standard can also be considered in future generations of intra-aircraft systems. Last but not least, the fact that UWB has become a mass market technology with its incorporation in smartphones (Apple and Samsung) makes future regulations move in favor of UWB more likely.

B. UNIQUE FEATURES
UWB offers robust high-rate communications and precise self-location. The latter is the most widespread use of this technology today. Inherent properties of the underlying impulse radio modulation adopt a very large transmission bandwidth (at least 500 MHz) resulting in a fine delay resolution. Many independent multipath components are thus resolvable at the receiver. This brings a high degree of delay diversity, whereby small-scale fading fluctuations can be almost completely eliminated. More recently, the use of UWB for data communication gained renewed interest in industrial environments, where experimental tests suggest that UWB is more robust than long-standing wireless technologies [56], [57]. These are promising results towards the performance of UWB in aircraft. UWB is also attractive from the security perspective discussed previously, as its noise-like signal is difficult to detect and more robust to jamming [58]. The latter is a stumbling block for the practical deployment of a wireless intra-aircraft network [25], [29]. Furthermore and also contributing to secure the network, the location properties of UWB can be exploited to verify location claims, a vulnerability identified in [25].

The standard UWB physical layer [42] specifies up to 27 Mbps, which supports the data rates of all intra-aircraft use cases currently under consideration. A small form factor and low energy consumption are also driving goals well posed for UWB because simple transmitters with low energy consumption are also driving goals well posed for UWB. The use of UWB in aircraft was explored in [50] to reduce wire redundancy in the wing-box system, and together with Wi-Fi and IEEE 802.15.3c with emphasis on reliability and security aspects related to interference and jamming [3]. Although power was not accounted for in the latter, it was observed that security risks are reduced by the low power spectral density of the UWB transmissions. To complement this, we stress on coexistence aspects and insights from an experimental testbed composed of off-the-shelf devices based on a different UWB specification (IEEE 802.15.4-2011 instead of ECMA-368).

A. COEXISTENCE
The coexistence of UWB with other wireless technologies is an active research field. A theoretical framework concerning how UWB and narrowband systems [51] outlines the conditions under which interference from UWB to narrowband systems can be approximated as Gaussian noise: Such approximation is accurate if the narrowband link experiences Rayleigh fading, or if several UWB pulses are received within each narrowband symbol. The Rayleigh assumption is reasonable for in-cabin propagation, and the pulse duration assumption holds for the timing of the relevant technologies (mainly LTE, Wi-Fi, and Bluetooth). Other studies like [52] focus on system-specific coexistence, where the impact of the cumulative interference from multiple UWB systems to the downlink of GSM and CDMA systems is discussed. Acceptable density bounds for UWB devices are derived that guarantee reasonable performance of the coexisting systems. Results on the coexistence of Wi-Fi systems with UWB are available in [53] and [54], where the latter presents theoretical emission limits for UWB devices interfering an IEEE 802.11n network.

FIGURE 2. Emissions in the vicinity of the WAIC band [12]. LTE bands (active over different geographical areas) as well as the location of the ISM bands where active services exist are shown for reference. Note that the UWB transmission over band 3 from the standard [42] does not introduce relevant interference to the mobile network nor ISM bands.

from protocols to implementations, indicate the adequacy of UWB to challenging propagation environments [44]–[49]. The use of UWB in aircraft was explored in [50] to reduce wire redundancy in the wing-box system, and together with Wi-Fi and IEEE 802.15.3c with emphasis on reliability and security aspects related to interference and jamming [3]. Although power was not accounted for in the latter, it was observed that security risks are reduced by the low power spectral density of the UWB transmissions. To complement this, we stress on coexistence aspects and insights from an experimental testbed composed of off-the-shelf devices based on a different UWB specification (IEEE 802.15.4-2011 instead of ECMA-368).
and Wi-Fi since it attains a better balance between data rate and power consumption, of critical importance for operation on ambiance energy.

The Wi-Fi specification 802.11ah aimed at IoT applications might also be attractive as it operates in less crowded bands [40], [41]. For the maximum 5 MHz globally available (resulting from the EU allocation), a throughput of almost 22 Mbps, similar to UWB throughput, can be achieved. However, there are two main drawbacks that we believe make its adoption unlikely in avionics. First, the fact that its spectrum is not globally harmonized (and bands might be restricted on aircraft as well) makes the perspective of global use for aircraft complex [40]. Second, its optimization for low power operation is based on restricted wake up time [41], [59]. This is an approach also taken in UWB but with much lower transmission powers. The power consumption of 802.11ah is thus significantly higher than that for UWB, turning the sustainable operation of nodes more challenging.

C. REGULATORY CONSTRAINTS AND SAFETY

Any wireless communication system must comply with the existing regulations regarding the allowed transmission bands and power levels. This is particularly challenging in the aviation industry as regulations on spectral bands can have significant differences over regions. UWB transmissions in particular are subject to specific restrictions. In the USA, the Federal Communications Commission specifies a maximum of $-41.3$ dBm emission level in any direction, although operation in aircraft is specifically not permitted. The same prohibition irrespective of the transmission band holds in Australia. In Europe, an emission of $-41.3$ dBm is allowed in the frequency region between 4.2 and 4.8 GHz (UWB channel shown in Figure 2). Japan is less stringent, as the same emission value holds for this band and for which interference mitigation techniques are not required.

Despite the complex situation of UWB regulation and the fact that global permission is still not achieved, we believe that if technical studies prove UWB to be a promising solution, they can contribute to revising current regulations towards a global convergence on the use of UWB in airplanes.

The fact that UWB transmissions are below the noise power level is a great advantage compared to most narrowband systems in terms of electromagnetic compatibility (EMC) and passenger health concerns (see, e.g., [60]). The International Civil Aviation Organization (ICAO) addressed issues with UWB early on [61]. The effects of UWB on safety are under the auspices of ICAO: “The international aviation community must ensure that the implementation of UWB technology does not cause interference to cause interference to radio spectrum used for aeronautical safety services.” [61]

D. EXPERIMENTAL TESTBED

Proof-of-concept results from our work on the development of an intra-aircraft WSN are presented to highlight the distinctive features of inside-aircraft propagation as well as the development challenges towards meeting the performance targets introduced in Section II.A.

Different to the contributions in [21], [22], [62]–[64], we do not conduct channel sounding based on laboratory instruments but rather test experimentally different performance aspects of a testbed composed of off-the-shelf transceivers. We believe that useful complementary insights can be obtained from our approach since the use of off-the-shelf equipment can expedite the aircraft certification process and their testing in harsh environments such as aircraft has not been fully explored yet. Specifically, we analyze scalability and timeliness through the impact of deployment positions, the assessment of the cabin particularities, and the latency and throughput trade-off characterization. Finally, we address the lifetime of the nodes in terms of their rate and energy harvesting requirements.

Our testbed is based on EVK-1000 development kits, which are IEEE 802.15.4-2011 compliant transceivers manufactured by Decawave [65] (now Qorvo). This testbed was deployed in the cabin of an Airbus A319 with 21 seatrows parked at Cotswold Airport in Cirencester, UK. We implemented a single cell (described in the network architecture on page 52915) and tested point-to-point link performance along the complete cabin length using a time division multiple access (TDMA) scheme.

From the deployed sensors, we recorded the received signal strength indicator (RSSI) values over time for all links. RSSI is a rough metric for the channel quality and it is in fact the metric likely to be used in practical implementations with hardware constrained nodes. We also kept track of the number of packets lost on each link. The error counts and link quality indicators are used for extracting insights into the impact of the node positioning and dimensioning of the cellular structure of the WSN. We measured the current consumption in transmit, receive, and sleep mode, as well as the attainable synchronization accuracy. In order to avoid any bias on power measurements, due to the practical non-isotropic radiation pattern from the nodes antennas, we measured the radiation pattern of our devices and adjusted the deployment accordingly.

1) IMPACT OF DEPLOYMENT POSITIONS

Figure 3 shows our proof-of-concept deployment to test the WSN functionality of a single cell: eighteen wireless sensor nodes communicate with a single data concentrator located at the front end of the passenger cabin hallway at 2.2 m height (ceiling). Channel access is organized into time slots and the data concentrator allocates slots to each node in a round robin fashion following TDMA. Nodes are always located in the middle seat, on both the left and right sides of the cabin, at seatrows 2, 5, and 8 (rows 1 to 6 correspond to business class with a seat separation of 0.9 m, and from row 7 the separation reduces to 0.7 m). At each employed seat, three nodes are deployed: one at the floor, one at the seat arm rest (0.9 m height), and another one at the top panel (1.65 m height). These correspond to the locations of the seat status
FIGURE 3. Experimental deployment in an Airbus A319, comprising EVK-1000 boards: (a) testing point-to-point communication performance along the complete length of the passengers’ cabin, and (b) and (c) implementing single-cell communication.

FIGURE 4. Recorded RSSI values over time for a single seat and three deployment positions of interest: floor, seat arm rest, and top panel (see Fig. 3 (c)). The left side shows the behavior when two persons are standing and walking along the hallway; the right side shows an empty cabin as reference.

The signal path loss function $PL(d)$ provides key information on the propagation environment. It can be expressed in dB (see for example [66]) as

$$PL(d) = PL(d_0) + 10\alpha \log_{10} \left( \frac{d}{d_0} \right) + \xi,$$

where $d$ represents the distance, $d_0$ is a reference measurement distance, and $\alpha$ is the path loss exponent that determines how severe is the signal attenuation with increasing distances. The term $\xi$ is a zero-mean Gaussian random variable that is incorporated to model the measurement error. To fit the model in (1) to our experimental RSSI measurements, we select $d_0$ as the distance from the data concentrator to seatrow 2. We compute a different $PL(d_0)$ for each height by averaging the results from the left and right sides of the cabin. We further distinguish between measurements with the empty cabin and those with two persons standing and walking along the hallway during the measurement time (see Figure 4). Overall, we partition our measurements into six segments: for the floor, arm rest, and top panel deployment heights, and for both the mobility and static setups in each case. Measurements are further processed to remove RSSI outliers deviating over 2.5 times the standard deviation of each segment. As can be seen from the static setup in Figure 4, there is a non-negligible measurement noise introduced by the commercial transceivers. Therefore, each value in the left-hand-side of (1) is given by the following sample mean

$$PL_k(d_j) = \frac{1}{N_i} \sum_i^N RSSI_i(d_j) \quad \text{for} \quad k = 1, \ldots, 3,$$

where indexes $k, j,$ and $i$ correspond to the deployment height, measurement distance, and slot measured, respectively, with $N_i$ being the number of slots measured at the given distance and height. Values from the left and right side of the cabin at each seatrow are averaged together. Our minimum mean square error fit of the data shows for the top panel nodes (LOS) an $\alpha$-value of 0.65 in line with the results reported in [64] and values between 1.33 and 1 for the floor and arm nodes (NLOS), respectively. The NLOS values are comparable but lower than the values in [63] and [64] for similar deployment conditions. We attribute differences to the Rake receiver architecture from our commercial transceivers.

To analyze the impact of mobility, we introduce the normalized variance metric

$$\sigma^2_{\text{norm}} = \frac{\sum_i(RSSI_i(d_j) - PL_k(d_j))^2}{N_i \cdot PL_k(d_j)},$$

which allows to quantify its effect for the three deployment heights, as shown in Figure 5. One main design challenge is highlighted in this figure: the impact of passenger mobility on the RSSI recorded is huge, with more than a five-fold variance increase for only two moving people. Nevertheless,
results obtained with a vector network analyzer in a similar environment (see [21], [22]) indicate that most of the impact from passengers is limited to those in the vicinity of the UWB transceiver. The path loss increase from an empty to a full cabin is only a few dB consistently in these two independent studies. In our experiments, as expected, the overall variance values are at highest for the floor position (as people’s legs more frequently obstruct the signal path) and at lowest for the top position (obstructed less often). In all cases, RSSI values show a significant power margin to the $-105 \text{ dBm}$ sensitivity of the commercial transceivers.

2) CABIN PARTICULARITIES

In order to investigate the particularities of the in-cabin propagation environment, we conducted point-to-point link measurements between two boards along the complete aircraft length (Figure 3 (a)). The data concentrator was located at the ceiling at the front end of the hallway, and a wireless node at increasing distances up to 24.6 m at the back of the crew compartment similar to the deployment positions in [21], [22], [62], [64]. These measurements enable us to explore coverage characteristics of the UWB devices in a complementary manner, accounting for the inaccuracies of hardware constrained transceivers. These are a key element for dimensioning the cell size and the required level of diversity (e.g., spatial, code).

The tunnel-like shape of the metal aircraft body favors signal reflections in contrast to what is observed in buildings and indoor office environments. The in-cabin wideband channel characterizations in [21], [22], [63], [64] reported this phenomena around different center frequencies from 2.45 to 10.6 GHz. It was observed that a waveguide effect (also reported in propagation along tunnels) occurs along the aircraft fuselage. Signal strength values do not monotonically decrease with distance. The implications on the system design of such a waveguide effect prompted us to quantify this phenomenon for our testbed. Figure 6 shows the RSSI and packet loss results from two measurements, one with the wireless node positioned at the armrest height along the hallway and another with the wireless node at the same height but at the middle seat. Each position was measured over 500 transmissions to record the average RSSI and packet loss rate. The RSSI behavior over distance (second order polynomial fit in the figure) is consistent with the results in [22], but with the location of the maximum power loss at significantly higher distances of 12 to 16 m instead of 7 to 10 m. This difference suggests that the distance at which the minimum reception power occurs depends on the aircraft body dimensions and needs to be evaluated for different aircraft.

The waveguide effect can be incorporated into an analytical channel model by augmenting (1) with a distance dependent path loss coefficient, as done in [21] and [63]. This allows to characterize the path loss behavior along the complete cabin length. Thus, for each distance we have

$$
\alpha(d) = \frac{\text{PL}(d) - \text{PL}(d_0) - \xi}{10 \log_{10} \left( \frac{d}{d_0} \right)},
$$

with the measurement at $d_0 = 2.5$ m as the reference point. Using (4), we can estimate the path loss along the cabin for each measurement distance by including the data from all smaller distances. Figure 7 shows the resulting estimates for the hallway and middle seats together with a linear fit to highlight the underlying trends. Different to [63], our testbed does not allow to distinguish the frequency and distance dependencies of the path loss. Nevertheless, the trend in Figure 7 is in line with those reported in [21] and [63].

Our results confirm the waveguide effect along the aircraft body with $\alpha$-values decreasing with distance. We can observe that this effect is stronger for the line-of-sight case (hallway), although it is also significant for the non-line-of-sight links (middle seat). These results affect the network structure design since the interference from far-away cells is
significant and needs to be appropriately handled. However, at the same time, this effect provides a way to enhance the network reliability if distant data concentrators cooperate for signal detection and security tasks. In both cases, the observed behavior influences the dimensioning of the network cells.

3) LATENCY AND THROUGHPUT TRADE-OFF

Most of the traffic in intra-aircraft applications is in the uplink direction (see Section II-B) with nodes transmitting sensed data to a data concentrator. The downlink channel is used for synchronization and network control functions like node discovery, configuration, and scheduling [57].

Uplink and downlink are time multiplexed as shown in Figure 8 with the downlink occupying a small fraction of the frame duration. The time between downlink slots defines the system latency. The number \( N \) and duration \( t_{UL} \) of uplink slots between downlink slots can be adjusted to meet a required latency. Although many short uplink slots result in lower latency, packets transmitted at the physical layer have a fixed overhead (i.e., preamble and header) that reduces the effective data throughput as their payload becomes smaller. This overhead amounts to \( 100\mu s \) in our implementation. Furthermore, our boards show a synchronization tolerance of around \( 40\mu s \) and a variable delay of up to \( 50\mu s \) when switching transceiver states. These tolerances force the insertion of \( 50\mu s \) guard intervals between slots to prevent collisions. With \( R_M = 6.8 \text{ Mbps} \), the effective throughput is

\[
R_{\text{eff}} = \frac{R_M N t_{UL}}{N(t_{UL} + t_g) + t_{DL}}.
\]

Figure 9 shows the trade-off between latency and throughput \( R_{\text{eff}} \) when accounting for the boards tolerances and the physical layer overhead. Smaller payloads reduce the latency at the cost of a reduced throughput. For very small payloads, a higher \( N \) significantly improves the throughput. However, as the packets become larger, the gain does not compensate the much longer latency. The latency-throughput operating point highly influences through the supported traffic volume the dimensioning of the network cells, mostly when the latency targets are tight. The vertical gap between traces results mostly from the compounded effect of the guard intervals.

4) LIFETIME AND SUSTAINABILITY

Radio activity consumes most of the nodes’ energy. Thus, we can estimate their lifetime and potential for sustainable operation (on a battery and environment energy) from it. The charge balance \( Q(t) \), in Coulomb, for a node is

\[
Q(t) = Q_B + \Delta Q_{\text{H}} t - (1 + \alpha) \Delta Q_{\text{R}} t.
\]

where \( Q_B \), \( \Delta Q_{\text{H}} \), and \( \Delta Q_{\text{R}} \) stand for the battery charge, the charge harvesting rate, and the radio discharge rate, respectively. Coefficient \( \alpha \) models a radio activity overhead due to the retransmission of failed packets, assumed to be 1% [67]. The transmission and reception of packets as well as the consumption on sleep periods contribute to the discharge

\[
\Delta Q_{\text{R}} = i_{tx} t_{UP} + i_{rx} t_{DL} + i_{\text{Sleep}}(t_f - t_{UP} + t_{DL}).
\]
with the current consumptions \( i_{tx} = 65 \text{ mA}, i_{rx} = 125 \text{ mA}, \) and \( i_{sleep} = 1 \mu \text{A} \) for our configuration [65]. Defining \( \ell \) as the time for which \( Q(t) = 0 \), the node lifetime results

\[
\ell = \frac{Q_R}{(1 + \alpha) \Delta Q_R - \Delta Q_H},
\]

shown in Figure 10 in terms of the nodes’ rate requirement. The blue trace (no harvesting) indicates that many low-rate monitoring applications and on-demand sensing can reach over ten years operation on a battery alone, which is a promising result. More rate-intensive use cases need to harvest energy from the environment to reach this lifetime, but we believe that the low power consumption of UWB makes the harvesting requirements feasible.

V. A LOOK INTO THE FUTURE

The aeronautical industry has a long-term vision dictated by the lifetime of an aircraft. Developments in intra-aircraft communications today should remain in force for at least seven to ten years. They hold strong implications for the wireless technology to be selected for implementation. Developments must cope with the requirements existing today as well as upcoming requirements during the following decade.

We see three focus areas that need to be advanced in parallel in the upcoming years. The first area is a deep investigation into the achievable throughput versus reliability performance across the network. In terms of network capacity, the reliability targets (assessed as packet loss rate) set a difficult constraint. Different diversity sources must be included to provide sufficient redundancy. Experimental results on the use of spatial diversity in combination with non-orthogonal multiple access techniques — which is a popular research topic for improving channel efficiency in general — are presented in [20]. Developments in intelligent reflecting surfaces can improve spectrum and energy efficiency by tweaking the wireless environment for intra-aircraft communications. The challenge being in terms of carrying these surfaces, which add weight and thus increase fuel consumption. In summary, however, the availability of experimental measurements in aircraft is still scarce and no widely accepted channel model exists to assist the system design. Experimental measurements are difficult to obtain due to economic and security reasons, but we believe that it is a necessary step considering the significant deviations found from well-known indoor propagation environments (Figure 6). These deviations must be modeled on practical usage conditions to translate them into an analytical behavior model.

A second area focuses on how to secure the deployed network. We have briefly addressed the current research trends in this area and highlighted how it approaches the more general problem of securing the IoT. A challenging twist in this regard is that most of the current approaches to security in aircraft imply a traffic overhead that might not be feasible to support. We believe that similar to the case of IoT, physical layer security concepts can strongly contribute to secure the intra-aircraft network, while relaxing the overhead requirements at the same time.

The third main area of focus should quantify the energy harvesting perspectives inside the airplanes. The next steps in this topic follow two directions: first, the power consumption of the nodes under regular operation as well as the power that can be harvested within the aircraft need to be measured and optimized, which is currently a very active topic from the source perspective [17], [32]–[36], [67]; second, network protocols need to be re-designed to account for the amount and availability characteristics of the available energy supplies. While this is a rather mature research field, its particularization for the aeronautical industry is not straightforward.

VI. CONCLUSION

We presented an overview of key aspects in intra-aircraft communications along with their communication requirements. Challenges for the design of wireless intra-aircraft networks were highlighted, with emphasis on security, coexistence with other systems, and power autonomy. UWB is a particularly fitting technology to support intra-aircraft communications due to its enumerated features, which make it stand out from competing technologies. International regulation aspects currently constraining the use of UWB have also been discussed. Subsequently, a proof-of-concept implementation of an UWB-based WSN has been described, deployed in an Airbus A319. The results from this testbed highlight the potential of UWB for intra-aircraft use and identify challenges ahead.

ACKNOWLEDGMENT

The authors would like to thank Vladimir Vukadinovic for his contributions in an early stage of this research, and Alan Clayton and his team at Cotswold Airport for their assistance in in-aircraft measurements.
REFERENCES

[1] K. Bur, P. Omiyi, and Y. Yang, “Wireless sensor and actuator networks: Enabling the nervous system of the active aircraft,” IEEE Commun. Mag., vol. 48, no. 7, pp. 118–125, Jul. 2010.

[2] H. Canaday, “War on wiring: A look at the payoffs and challenges of removing wires from airplanes,” Aerosop. Amer., vol. 55, no. 5, pp. 24–27, May 2017.

[3] D.-K. Dang, A. Mifdaoui, and T. Gayraud, “Fly-by-wireless for next generation airplane health data,” in Proc. IFIP Wireless Days, Nov. 2012, pp. 1–8.

[4] E. Dinc, M. Vondra, S. Hofmann, D. Schupke, M. Priyttz, S. Bovelli, M. Frodigh, J. Jander, and C. Cavdar, “In-flight broadband connectivity: Architectures and business models for high capacity air-to-ground communications,” IEEE Commun. Mag., vol. 55, no. 9, pp. 142–149, Aug. 2017.

[5] R. K. Rajasekaran and E. Frew, “Cyber-security challenges for wireless networked aircraft,” in Proc. Integ. Commun., Netw. Survell. Conf. (ICNS), Apr. 2017, p. 3.

[6] K. Sampigethaya, R. Poovendran, S. Shetty, T. Davis, and C. Royalty, “Future E-enabled aircraft communications and security: The next 20 years and beyond,” Proc. IEEE, vol. 99, no. 11, pp. 2040–2055, Nov. 2011.

[7] S. Lintelman, R. Robinson, M. Li, L. Bushnell, R. Poovendran, and K. Sampigethaya, “Secure wireless collection and distribution of commercial airplane health data,” IEEE Aerosp. Electron. Syst. Mag., vol. 24, no. 7, pp. 14–20, Jul. 2009.

[8] Technical characteristics and operational objectives for wireless avionics in-tra-communications (WAIC), document ITU-R M.2325, Jun. 2015.

[9] A. S. Zahmatsi, X. Fernando, and H. Kojori, “Emerging wireless applications in aerospace: Benefits, challenges, and existing methods,” in Proc. 4th Annu. Canues Fly Wireless Workshop, Jun. 2011, pp. 1–4.

[10] J. Zhang, T. Chen, S. Zhong, J. Wang, W. Zhang, X. Zuo, R. G. Maund, and L. Hanzo, “Aeronautical Ad Hoc networking for the Internet-above-the-clouds,” Proc. IEEE, vol. 107, no. 5, pp. 868–911, May 2019.

[11] Technical characteristics and protection criteria for wireless avionics in-tra-communications system, document Rec. ITU-R M.2067-0, Feb. 2015.

[12] S. A. P. Kumar and B. Xu, “Vulnerability assessment for security in aviation cyber-physical systems,” in Proc. IEEE 4th Int. Conf. Cyber Secur. Cloud Comput. (CSCloud), Jun. 2017, pp. 145–150.

[13] K. Sampigethaya, R. Poovendran, and L. Bushnell, “Secure operation, control, and maintenance of future E-enabled airplanes,” Proc. IEEE, vol. 96, no. 12, pp. 1992–2007, Dec. 2004.

[14] R. N. Akram, K. Sampigethaya, K. Mayes, P.-F. Bonnefie, D. Sauveron, and S. Chaumette, “Security and performance comparison of different secure channel protocols for avionics wireless networks,” in Proc. IEEE/AIAA 35th Digit. Avionics Syst. Conf. (DASC), Sep. 2016, pp. 1–8.

[15] E. Thayer, “Adversarial testing to increase the overall security of embedded systems: A review of the process,” IEEE Control Syst., vol. 37, no. 2, pp. 104–108, Apr. 2017.

[16] R. N. Akram, K. Sampigethaya, K. Mayes, P.-F. Bonnefie, D. Sauveron, and S. Chaumette, “Efficient, secure and trusted channel protocol for avionics wireless networks,” in Proc. IEEE/AIAA 35th Digit. Avionics Syst. Conf. (DASC), Sep. 2016, pp. 1–10.

[17] Y. Guan and X. Ge, “Distributed secure estimation over wireless sensor networks against random multichannel jamming attacks,” IEEE Access, vol. 5, pp. 10858–10870, 2017.

[18] M. Bafleure and J.-M. Dilhac, “Towards energy autonomy of wireless sensors in aeronautics applications: SMARTER collaborative project,” in Proc. IEEE Int. Conf. Green Comput. Commun., Aug. 2013, pp. 1668–1672.

[19] J.-M. Dilhac and M. Bafleure, “Energy harvesting in aeronautics for battery-free wireless sensor networks,” IEEE Aerosp. Electron. Syst. Mag., vol. 29, no. 8, pp. 18–22, Aug. 2014.

[20] L. V. Allmen, G. Baillieul, T. Becker, J.-D. Decotignie, M. E. Kiziroglou, C. Leroux, P. D. Mitcheson, J. Müller, D. Piguet, T. Tóth, A. Weisser, S. W. Wright, and E. M. Yeatman, “Aircraft strain WSN powered by heat storage harvesting,” IEEE Trans. Ind. Electron., vol. 64, no. 9, pp. 7284–7292, Sep. 2017.

[21] A. Elefsoiniotis, N. Kokorakis, T. Becker, and U. Schmid, “Performance of a low temperature harvesting device for powering wireless sensor nodes in aircrafts applications,” in Proc. 17th Int. Conf. Solid-State Sens., Actuators Microsyst., Jun. 2013, pp. 2276–2279.

[22] J. Estrada, P. Zurek, and Z. Popovic, “Harvesting of aircraft radar altimeter sidelobes for low-power sensors,” in Proc. Int. Appl. Comput. Electromag. Soc. Symp. (ACES), Mar. 2018, pp. 1–2.

[23] M. Mohajerizadeh, Y. Savaria, and M. Sawan, “Harvesting energy from aviation data lines: Implementation and experimental results,” IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 65, no. 6, pp. 2084–2087, Jun. 2018.

[24] C. Sergiou, V. Vassiliou, and K. Christou, “RF energy harvesting in wireless sensor networks for critical aircraft systems—An experimental approach,” in Proc. IEEE Int. Conf. Wireless Space Extreme Environ. (WSEE), Sep. 2016, pp. 180–183.

[25] J. Zhang, S. Hashemi, M. Karimian, Z. Koubaa, and M. Sawan, “A novel power harvesting scheme for sensor networks in advanced aviation applications,” in Proc. IEEE 20th Int. Conf. Electron., Circuits, Syst. (ICECS), Dec. 2013, pp. 921–924.

[26] C. Vanhecke, L. Assouere, A. Wang, P. Durand-Estebbe, F. Caignet, J.-M. Dilhac, and M. Bafleure, “Multisource and battery-free energy harvesting architecture for aeronautics applications,” IEEE Trans. Power Electron., vol. 30, no. 6, pp. 3215–3227, Jun. 2015.

[27] A. Dwivedi, S. Zoppi, W. Kellerer, F. Neubauer, and D. Schupke, “Wireless avionics in-tra-communications (WAIC) QoS measurements of an ultra wideband (UWB) device for low-data rate transmissions,” in Proc. AIAA/IEEE 39th Digit. Avionics Syst. Conf. (DASC), Oct. 2020, pp. 1–8.

[28] S. Aust, R. V. Prasad, and I. G. M. Nienmeegers, “Outdoor long-range WLANs: A lesson for IEEE 802.11 ah,” IEEE Commun. Surveys Tuts., vol. 17, no. 3, pp. 1761–1775, 3rd Quart., 2015.

[29] T. Adame, A. Bel, B. Bellalta, J. Barcelo, and M. Oliver, “IEEE 802.11AH: The WiFi approach for M2M communications,” IEEE Wireless Commun., vol. 21, no. 6, pp. 144–152, Dec. 2014.

[30] Standard for Local and Metropolitan Area Networks—Part 15.4: Low-Rate Wireless Personal Area Networks, IEEE Standard 802, Sep. 2011.

[31] N. Raharya and M. Suryanegara, “Compatibility analysis of wireless avionics in-tra-communications (WAIC) to radio altimeter at 4200–4400 MHz,” in Proc. IEEE Asia Pacific Conf. Wireless Mobile, Aug. 2014, pp. 17–22.

[32] Standard for Local and Metropolitan Area Networks—Part 15.4: Low-Rate Wireless Personal Area Networks, IEEE, Sep. 2011.
J. F. Schmidt, D. Chernov, M. Pauritsch, and C. Bettstetter, “Study of wireless communications in airplanes: Challenges and the Case for UWB wireless systems. He received the Best Paper Award from ACM SIGSIM.

JORGES SCHMIDT received the B.Sc. and D.Sc. degrees in electrical engineering from the Universidad Nacional del Sur, Argentina, in 2005 and 2011, respectively. In 2012, he was with the University of Vigo, Spain, until he joined the Institute of Networked and Embedded Systems group, University of Klagenfurt, Austria, in 2014. Since 2016, he has been a Senior Researcher with Lakeside Labs GmbH, Austria. His research interests include interference modeling and management in wireless communications and robotics.

DANIEL NEUHOLD received the master's degree in information and communications engineering from the University of Klagenfurt. He is currently pursuing the Ph.D. degree in robust UWB sensor networks for airplanes and industrial applications. He was invited as a Guest Researcher with the University of Southern California (USC), in 2018. He continued as a Research and Teaching Staff Member in Klagenfurt with interests in wireless communications and high-precision indoor localization.

CHRISTIAN BETTSTETTER (Senior Member, IEEE) received the Dr.-Ing. degree (summa cum laude) in electrical and information engineering from TUM München, Munich, Germany, in 2004. He is currently a Professor and the Head of the Institute of Networked and Embedded Systems, University of Klagenfurt, Austria, and the Scientific Director of Lakeside Labs GmbH, Austria. His research interests include wireless connectivity and self-organization with application to telecommunication networks for airplanes and industrial applications. He was invited as a Guest Researcher with the University of Southern California (USC), in 2018. He continued as a Research and Teaching Staff Member in Klagenfurt with interests in wireless communications and high-precision indoor localization.

JIRKA KLAUE received the Diploma in computer science from the Technical University of Berlin, in 1999. Afterwards, he worked on wireless video transmission at the Telecommunication Networks Group and DResearch. He is currently a Researcher with Airbus Group Innovations in field of wireless communications. He is also the Co-Founder of a software company for web-based database applications. At Airbus, he participated in research projects founded by the EU, BMBF, also works on reliable and time-critical wireless sensor networks.

DOMINIC SCHUPKE (Senior Member, IEEE) studied Electrical Engineering and Information Technology at RWTH Aachen and Imperial College London. He received the Dr.-Ing. degree (summa cum laude) from the Technical University of Munich (TUM). He is currently a Research Leader of Reliable Communication Networks, focusing on Wireless Communications at Airbus, Munich, Germany. He is also a Lecturer of Network Planning with TUM. Prior to Airbus, he worked with Nokia, Siemens, and TUM. He is the author or coauthor of more than 140 journal and conference papers (Google Scholar H-index 30). His research interest includes aerospace networks.

VOLUME 9, 2021
52925