Wireless Avionics Intracommunications: A Survey of Benefits, Challenges, and Solutions

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***Abstract*—In the aeronautics industry, wireless avionics intracommunications (WAICs) have a tremendous potential to improve efficiency and flexibility while reducing weight, fuel consumption, and maintenance costs over traditional wired avionics systems. This survey starts with an overview of the major benefits and opportunities in the deployment of wireless technologies for critical applications in an aircraft. The current state of the art is presented in terms of system classifications based on data rate demands and transceiver installation locations. We then discuss major technical challenges in the design and realization of the envisioned aircraft applications. Although WAIC has aspects and requirements similar to mission-critical applications of industrial automation, it also has specific issues, such as wireless channels, complex structures, operations, and safety of the aircraft that make this area of research self-standing and challenging. Existing wireless techniques are discussed to investigate the applicability of the current solutions for the critical operations of an aircraft. Specifically, IEEE 802.15.4-based and Bluetooth-based solutions are discussed for low data rate applications, whereas IEEE 802.11-based and UWB-based solutions are considered for high data rate applications. We conclude the survey by highlighting major research directions in this emerging area.**

***Index Terms*—Industrial wireless networks, mission-critical communications, real-time systems, wireless avionics intracommunications (WAIC).**

I. Introduction

TRADITIONALLY, the aircraft control systems rely on expensive wired fieldbus networks to guarantee the flight safety requirements [1], [2]. Wired fieldbus costs include the cable harness design, the labor-intensive cable manufacturing, and the operating and maintenance costs of fibers and connectors [3]–[5]. In particular, the critical flight control systems require complex redundant fieldbus channels where the channels are physically and electrically separated from each other to improve fault tolerance [6]. For instance, a large commercial transport airplane like Boeing 747 includes roughly 228 km of wire, which weighs approximately 1587 kg [4]. Furthermore, recent advanced technologies, such as micro sensors and integrated modular avionics architecture need even more bandwidth and more flexible fieldbus topologies [7], [8]. We need a fundamentally new network infrastructure to reduce installation and maintenance costs and environmental impacts while meeting the safety requirements for next-generation avionics systems [9].

As one of the novel solutions, the aviation industry strives to use wireless technologies in both current aircraft upgrades and new aircraft designs. Wireless avionics intracommunication (WAIC) systems can significantly improve the operational efficiency and flexibility over current wired systems on the aircraft [2], [10], [11]. WAIC is restricted to applications related to secure, reliable, and effective aircraft operations, such as structural health monitoring, sensing, control, voice, video, and fieldbus communications, as defined by the International Civil Aviation Organization (ICAO)[1] [2]. WAIC must support extremely broad services, not only typical monitoring applications using wireless sensor networks (WSNs) but also the time-critical and data-demanding applications. WAIC systems are not designed to provide communications for in-flight entertainment or with consumer devices carried onboard the aircraft. Furthermore, it does not support any aircraft-to-ground, aircraft-to-aircraft, and aircraft-to-satellite communications.

Some companies, such as Honeywell and Bombardier developed and applied wireless sensing systems as the *Fly-by-Wireless* prototype for aerospace applications [12]–[14]. They have used wireless systems as a backup to traditional wired systems for the fault-tolerant design since different techniques are more robust against common mode failures at certain critical damage. Spinning out of the NASA related work, Invocon developed the wireless instrumentation system to improve reliability for various flight applications, including wireless control [15]–[17]. They have already applied a

Manuscript received September 9, 2020; revised October 28, 2020; accepted November 12, 2020. Date of publication November 18, 2020; date of current version May 7, 2021. The work of Pangun Park and Junghyo Nah was supported in part by the Basic Research Laboratory of the National Research Foundation (NRF) under Grant NRF-2020R1A4A2002021, and in part by the Institute of Information and Communications Technology Planning and Evaluation funded by the Korea Government under Grant 2020-0-00187. *(Corresponding author: Pangun Park.)*

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Digital Object Identifier 10.1109/JIOT.2020.3038848

[1]The ICAO develops standards and manuals to ensure safety and growth for civil aviation.

wireless sensing system to the space shuttle of NASA, where three wireless sensors monitor temperature and report back to a controller. NASA also obtained the mechanical motion of the station while coupled to the space shuttle using wireless communication from external sensors [17]. In 2008, Gulfstream aerospace corp. has successfully completed the feasibility test of the fly-by-wireless concept on its G550 aircraft using Invocon solutions as a purely backup system [10], [18]. Securaplane developed a wireless communication-based emergency lighting system to provide illumination and signal for aircraft evacuation in an emergency [19]. The wireless emergency lighting system has been applied in the Boeing 787 to save weight over wired systems.

Because WAIC systems necessarily operate worldwide and cross-national borders due to the international nature of air travel, different international organizations, government agencies, and the aviation industry have collaborated for the development, classification, and standardization of WAIC through the Aerospace Vehicle Systems Institute (AVSI), since 2008. Several manufacturers, such as Airbus, BAE Systems, Boeing, Honeywell, Thales, NASA, United Technologies are involved in the technical development of the WAIC system within AVSI. In particular, AVSI has extensively investigated the total spectrum demand to support various WAIC applications and has analyzed the compatibility and interference issues with existing aeronautical radionavigation service below 15.7 GHz [20]. In 2015, the International Telecommunication Union—Radiocommunication (ITU-R) finally announced the 4.2–4.4 GHz band as the primary spectrum band for WAIC systems at the world radio conference [21]. Hence, the Federal Aviation Administration, European Union Aviation Safety Agency, and ICAO rely on the assigned frequencies to develop and deploy WAIC systems. Furthermore, AVSI supports the laboratory testing and coordinates the development of a standard and recommended practice through ICAO to provide the technical basis for certification of future WAIC systems.

Despite the importance of the area, there are no previous works in the literature that rigorously and adequately describe opportunities and challenges in designing efficient WAIC systems from the communication point of view. This survey aims to provide an overview of the WAIC framework, main challenges, and existing related works to design, analysis, and deployment of WAIC systems. The major contributions of this article are as follows.

1) We provide a general overview of the aircraft systems, including reference structures and avionics systems in Section II.
2) We discuss the major benefits of WAIC system over traditional fieldbus infrastructure for avionics systems in Section III.
3) We present the case studies and the current state-of-the-art WAIC frameworks in Section IV.
4) We provide the major technical challenges for realizing the envisioned critical avionics applications using WAICs in Section V. As one of the most challenging tasks, we emphasize the characterization of wireless channels in WAIC environments from different points of view in Section VI.
5) We discuss closely related wireless techniques as potential candidates for WAIC systems in Section VII.
6) Finally, we conclude this survey by outlining promising research directions in Section VIII.

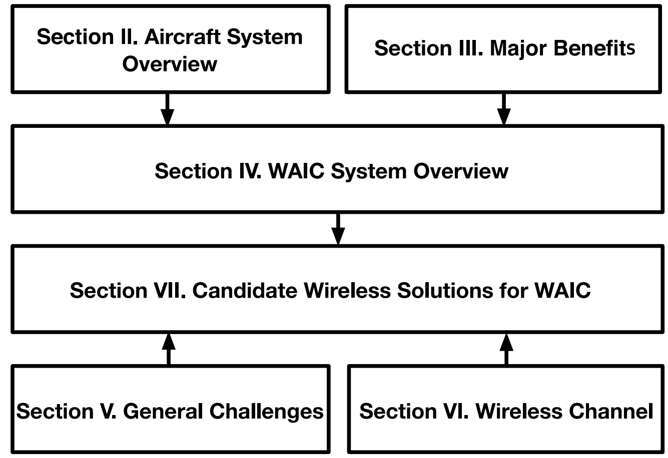

Fig. 1. Overall organization of this article: overview of aircraft systems in Section II, major benefits using WAIC in Section III, representation of the different WAIC systems in Section IV, major technical challenges in Sections V and VI, and existing related works illustrated in Section VII.

Fig. 1 summarizes the major relationships between overview of aircraft systems in Section II, major benefits using WAIC in Section III, representation of the different WAIC systems described in Section IV, major technical challenges analyzed in Sections V and VI, and existing related works illustrated in Section VII. To the best of our knowledge, this is the first study that thoroughly discusses the main benefits, technical challenges, and design principles to develop and deploy WAIC systems.

II. Aircraft System Overview

This section briefly describes a reference aircraft model and avionics systems.

A. *Reference Aircraft Structure*

Fig. 2 illustrates the main structural parts of a typical passenger aircraft with the major components and various compartments [2]. Most aircraft structures consist of a fuselage, an empennage, a powerplant, wings, and landing gears [22]. The fuselage is the centrally located main part, including the cockpit, cabin, and cargo compartments. The empennage includes the vertical and horizontal stabilizers at the entire tail part. These movable surfaces are used to control the horizontal rotation and the vertical rotation of the aircraft. The wings are the primary lifting surfaces attached to each side of the fuselage, including several critical actuators, such as ailerons, slats, and flaps to support the flight control systems. The powerplant encompasses all engine components, the propeller, and electrical system, such as nacelles and auxiliary power unit compartment, as shown in Fig. 2. The landing gear consists of wheels and struts to support the mobility on the ground. The critical actuators of flight controls are mainly located in the wings and tail section of aircraft, while the control-related

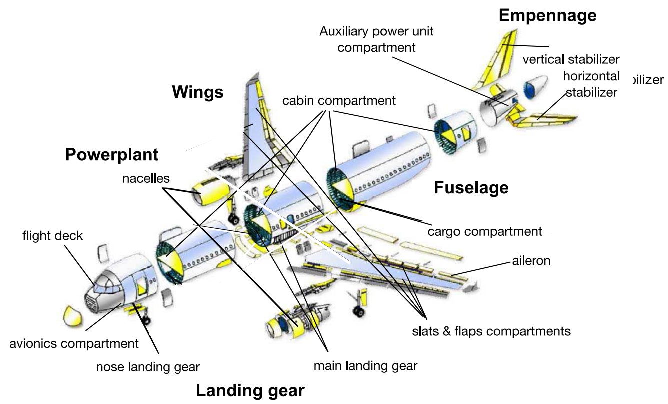

Fig. 2. Main components of a typical passenger aircraft with multiple compartments [2]. Most aircraft structures consist of a fuselage, an empennage, a powerplant, wings, and landing gears [22].

sensors, such as speed sensors are installed around nacelles and fuselage [22], [23]. In addition, structural health monitoring sensors are commonly installed on the main structure of aircraft, including wings and fuselage [24]. Hence, wireless transceivers of the WAIC system are mounted at various locations both inside and outside the airframe.

The commercial aviation industry considers the passenger aircraft of Fig. 2 as the main target of WAIC [2]. A typical passenger aircraft between 150 to 220 seats are considered as the reference aircraft to analyze the requirements [2], [25]. The overall length of this typical passenger aircraft is between 31.5 and 44.5 m. Hence, the maximum range between transmitter and receiver is about 50 m. Some recent unmanned aircraft and military aircraft do not have cabin compartment and nacelles in contrast to the typical structure of the passenger aircraft [22]. However, they still have similar major components of Fig. 2. Hence, the reference model is the most general structure of the typical aircraft since it sufficiently represents other aircraft types with minor modifications.

B. Avionics System

Avionics systems of civilian aircraft are grouped into a number of categories dependent on aircraft operations [26].

1) *Flight Control System:* The flight control generally consists of inner control loops and outer control loops. The inner control loop maintains aircraft stability while still achieving a fast response to disturbances. For example, the flight control system dampens the oscillations of the aircraft to improve passenger comfort. On the other hand, the outer control loop keeps a particular attitude and heading of the aircraft.
2) *Flight Management System:* The flight management system provides guidance and navigation with the optimal altitudes and speeds along the route.
3) *Engine Control:* The engine control includes functions to monitor the temperature, maintain smooth intake for condition changes, and ensure the correct relationship between pressure compressors of engines.
4) *Utilities Management System:* The aircraft utilities system handles hydraulics and fuel management, air-conditioning, oxygen control, and emergency power.

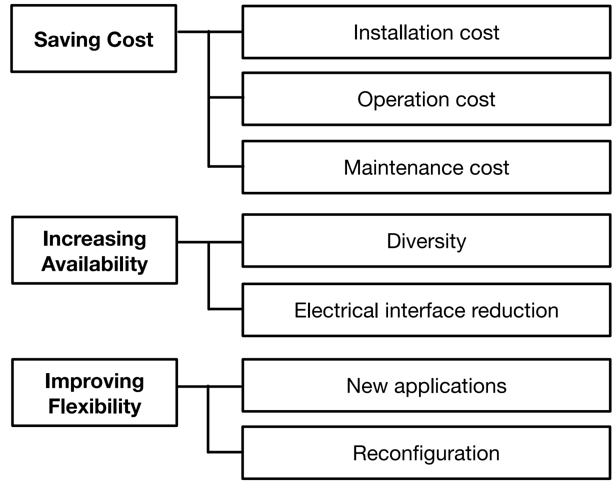

Fig. 3. Major benefits of WAIC systems grouped into three categories, namely, saving cost, increasing availability, and improving flexibility.

5) *Health Management Systems:* It mainly provides the monitoring information of strain gauges mounted around the aircraft and engine state variables, such as speeds, torques, and vibration levels.
6) *Entertainment Systems:* While it only applies to commercial aircraft, it is still important since it is one of the most data-demanding applications.

The typical avionics systems include not only heterogeneous functions but also a large number of subsystems with the complex interconnections.

III. Major Benefits

By replacing cables, WAIC offers competitive advantages, such as saving cost in terms of fuel consumption, installation, and maintenance, and improvement of reliability, flexibility, and scalability [10], [27], [28]. We classify the main benefits into three categories, namely, saving cost, increasing availability, and improving flexibility, as shown in Fig. 3. In the following, we elaborate more on the details about the major advantages of using WAIC systems.

A. Saving Cost

The installation, operation, and maintenance costs of cabling result in considerable pressure on the aircraft manufacturer and the airline operators [1], [29]. Due to the expense of materials and labor, the cost of installing sensors and fieldbus is likely not decreasing in the future.

One of the critical factors to develop a new aircraft is the wiring harness design [3]. In fact, the typical cost of the sensor installation is usually several times the actual cost of the sensor module itself. The developers must indicate and determine the complicated paths onboard the aircraft for kilometers of wire. The redundant wiring must ensure separate routing paths so that redundant circuits are not affected by a single point failure [10]. As the safety demand becomes strict, the cable weight increases due to the higher redundant resource requirements. Furthermore, the fault diagnosis within an advanced high-speed fieldbus network requires highly skilled technicians [30].

For instance, the total cabling weights of A320/B737 and A350/B787 are around 15% and 20% of the total weight of aircraft, respectively, [3], [10]. In each aircraft, the related costs, including manufacturing and installation, are approximately \$2200 per kilogram, resulting in a cost varying from \$14 million for A320/B737 to \$50 million for A350/B787 [10]. Cabling cost further increases for new generation aircraft, such as the A380 because of the longer cables. In A380, the extremely long cable of around 500 km is the main reason for the cost overruns and production delays, estimated at \$2 billion.

Wireless networks are an appealing technology since they can substantially decrease the time and cost of cable harness design and installation, and eventually, life-cycle costs of aircraft. Since wireless links provide redundant connectivity without specific redundant cables, it is a cost-effective solution for various types of aircraft. The price of wireless sensors and network devices is rapidly coming down following Moore's Law [31]. Furthermore, it is estimated that wireless communication can substantially decrease fuel consumption by 12% as a result of the weight reduction [10].

B. Increasing Availability

Avionics systems must provide high availability and determinism in the flight control systems to avoid catastrophic consequences, such as explosions and human losses [32], [23]. Wiring is a major source of maintenance and failure cost since it can affect the immunity of the interconnected system by inducing more than 50% of electromagnetic interference (EMI) within the aircraft [1], [3]. Such defects mainly occur at interface components, such as connectors, pins, and sockets and are extremely difficult to resolve and repair [1]. Several aircraft, including TWA 800 and Swissair 111, have been lost in the past due to wiring failures [33]. Due to wiring discrepancies, the U.S. Navy has 78 nonmission capable aircraft, about 27 365 flight hours between aborts in 2005 [1]. A wireless system can improve availability by substantially reducing electrical interfaces of the system.

Redundant components of cable harnesses are the main techniques to achieve a fault-tolerant aircraft design [6], [32]. However, duplicated cables using identical technology are generally vulnerable to common failures, such as lightning strike or fire. The wireless system as a backup to a typical fieldbus system provides redundancy through diverse techniques. It essentially offers the cost-effective built-in redundancy instead of complicated wired connections to the avionics systems.

C. Improving Flexibility

WAIC can support some new applications, such as monitoring rotating units, enabling mobile workers for maintenance, and integration of nontraditional signals, including voice, image, and video [28]. In particular, WAIC can collect information from where it was technically infeasible. For instance, one interesting application is the bearing monitoring of engine rotators, that cannot be performed with wiring harnesses [34].

Due to significant pressure changes, the fuselage health is the critical factor in guaranteeing the long average lifespan of civil aircraft, which typically exceeds 25 years [10]. Throughout the life-cycle of aircraft, WAIC could considerably reduce the complexity and cost to mount new sensors and allow easier system modifications [10]. For example, on-board sensors monitor lightning or other environmental damage during the flight operation. By using WAICs, it is not necessary to route the fieldbus cable to the dedicated controller from each sensor and actuator [27]. Furthermore, it supports flexible cabin configurations for more customized subsystems.

IV. WAIC System Overview

This section provides a motivating example and an overview of the state-of-the-art WAIC framework. We classify the WAIC systems based on the data rate demand and transceiver installation location of the AVSI standard [25].

Fig. 4 presents the conceptual WAIC network consisting of a large number of wireless devices and a wired backbone. Wireless devices include various sensors, actuators, and relay nodes of an aircraft. WAIC must support heterogeneous applications from monitoring systems to flight control systems, such as structural health monitoring, sensing, control, voice, video, and fieldbus communications. The heterogeneous applications include both low data rate applications, such as temperature measurements in cabins and high data rate applications, such as video surveillance [31], [35]. The heterogeneous software used in aircraft systems has various criticality levels and operational requirements. The software level, called the development assurance level (DAL), classifies various safety-critical software into five levels based on the impacts of system failure [36]. Table I shows five classes of the safety-critical software in avionics systems.

A. Motivating Flight Control Example

As an illustrative example of WAICs, flight control is considered to be one of the most challenging real-time tasks in avionics systems. Fig. 4 shows the main control surfaces and the communicating sensors of flight control systems on an aircraft. We emphasize the main sensors and actuators located around the fuselage, wings, and empennages in blue and red, respectively. Time-critical sensing (resp. actuating) data must be delivered from the sensors to controllers (resp. from controllers to the actuators). The flight control computers compute control signals and send the commands to ailerons, elevators, and a rudder in order to provide roll, pitch, and yaw. For larger aircraft, multiple computer systems consist of elevator aileron, spoiler elevator, and flight augmentation computers, such as A320. The state measurements of air data sensors and inertial sensors are used for both the inner and outer loop of flight control systems. Typical flight control sampling rates are in the range of 30–100 Hz [12]. However, there is no absolute sampling rate demand that can suit all types of aircraft due to

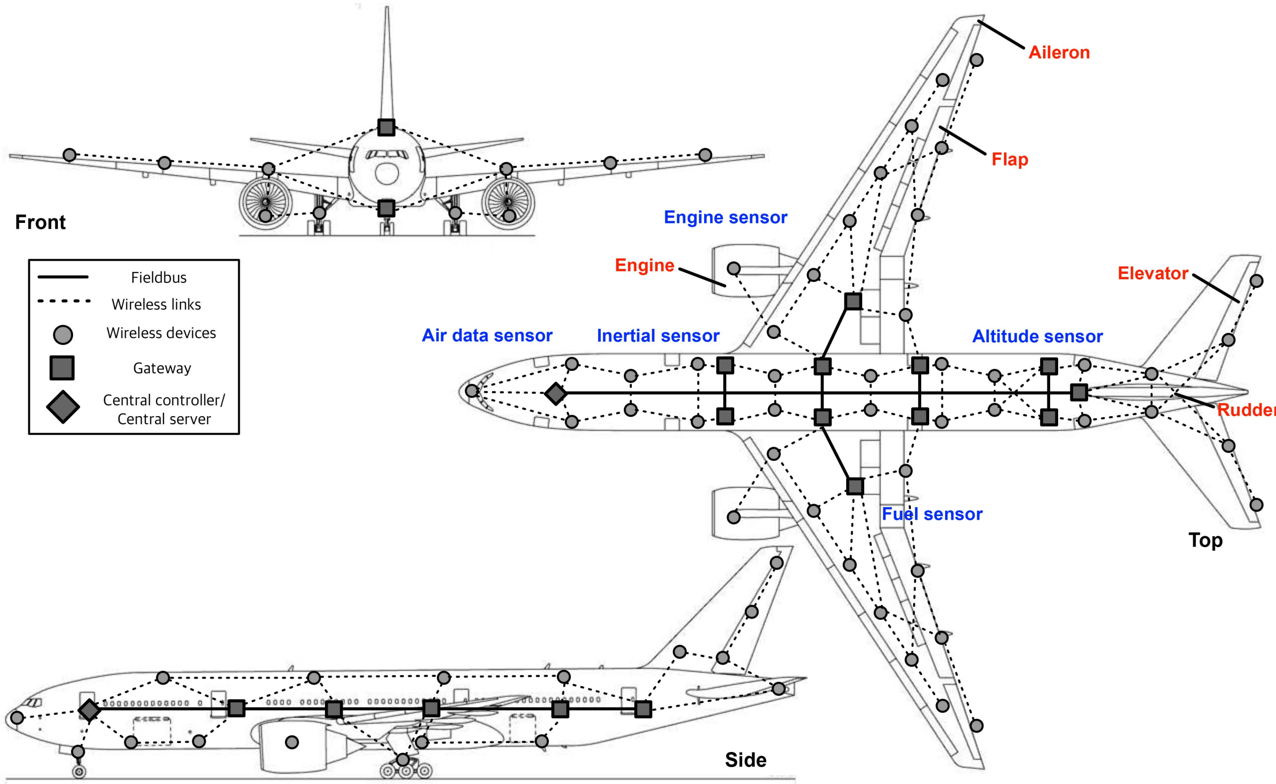

Fig. 4. Reference WAICs systems composed of a large number of wireless devices and wired backbone for a typical passenger aircraft. We emphasize the main sensors and actuators located around the fuselage, wings, and empennage in blue and red, respectively.

the sampling rate dependency on the flight dynamics and the control algorithms.

B. WAIC System Classification

The current architecture of relatively new aircraft, such as the A350 and A380, mainly consists of two different networks, namely, high data rate and low data rate fieldbuses [32], [37]. A high data rate fieldbus, such as Ethernet-based avionics full duplex switched Ethernet (AFDX) [38] and optical fiber-based ARINC818 [39] and MIL-STD-1773 [40] is used as a backbone network in order to connect the avionics subsystems of aircraft. In each avionics subsystem, a low rate data fieldbus, such as ARINC429 [41] and MIL-STD-1553 [42] directly connects sensors and actuators.

By considering the existing fieldbus and the signal attenuation, AVSI categorizes WAIC systems based on two features, namely, data rate requirement (high and low) and transceiver location (inside and outside the airframe) [25]. Fig. 5 shows four classes, namely, “low data rate inside (LI),” “low data rate outside (LO),” “high data rate inside (HI)” and “high data rate outside (HO).” Table II lists the main characteristics and requirements of four classes, including further attributes associated with each class. The classification threshold between low and high data rate applications is 10 kb/s [25]. Most low data rate nodes measure scalar data, such as strain, pressure, temperature, and humidity. These devices are usually resource-constrained on computation, storage, and energy. High data rate nodes transmit high-resolution measurements, such as engine status, image, and video.

TABLE I

DAL Indicates the Level of Safety-Critical Software Function of an Aircraft Based on the Safety Assessment Process in DO-178B [36]. DO-178B Is a Guideline for the Safety-Critical Software Certification Used in Avionics Systems

Level	Failure condition	Failure rate
A	Catastrophic	10^{-9}/h
B	Hazardous	10^{-7}/h
C	Major	10^{-5}/h
D	Minor	10^{-3}/h
E	No effect	n/a

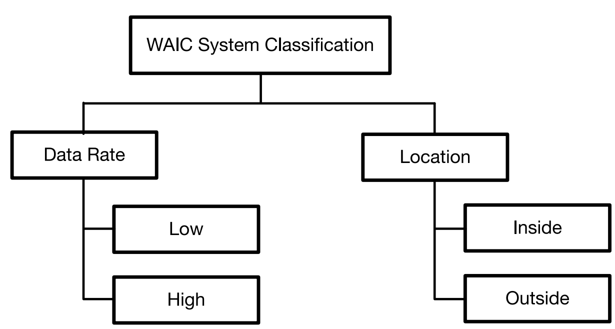

Fig. 5. WAIC system classification based on the two features, namely, data rate requirement (high and low) and transceiver location (inside and outside the airframe) [25].

The classification of the installation location depends on the radio-frequency (RF) attenuation of the airframe material. The ITU-R report classifies the nodes as “Inside” only when surround material incurs significant RF attenuation (e.g., when the

TABLE II
TECHNICAL CHARACTERISTICS OF FOUR CLASSES FOR WAIC SYSTEMS [25]

	Low data rate inside	Low data rate outside	High data rate inside	High data rate outside
Aggregate average data rate of network (kbit/s)	394	856	18,385	12,300
Range of average data rate per link (kbit/s)	0.01-0.8	0.02-8	12.5-1,600	45-1,000
Peak data rate per link (kbit/s)	1	8	4,800	1000
Number of nodes	4,150	400	125	65
Installation domain	inside	outside	inside	outside
Maximum distance between TX and RX (meter)	15	15	15	15
Typical channel	NLOS	LOS/NLOS	LOS/NLOS	LOS
Application	sensing and control (cabin temperatures, pressure control, smoke, door)	sensing and control (temperature, pressure, structural stress, landing gear)	sensing and communication (engine, avionics data bus, voice/video/image)	sensing and control (structure, vibration control, voice/video/image)
Dominant DAL levels	C/D	A/B	B/C	B/C
Spectrum requirements per aircraft (MHz)	35		53	
Maximum transmit power (mW)	10		50	
Receiver sensitivity (dBm)	-91		-77	

surround material is metal). Depending on a particular operation, some applications may be categorized differently. For instance, when the gear is extended, landing gear sensors will be changed to the outside class from inside one. As shown in Table II, most transmissions of general aircraft are inside the aircraft structure (e.g., fuselage and wings). However, some critical sensors and actuators still operate outside, at least for some time.

We provide detailed descriptions of each class in the following sections.

1) LI Class: The LI class is characterized by two main attributes, namely, low data rate (<10 kb/s) and transceiver installation inside metal-like enclosures. These applications include wireless sensing and control signals of slowly varying physical processes, such as smoke sensors, door position sensors, and pressure control. Most LI applications belong to level C and D except some critical smoke and fire detection sensors of Table I.

Most of the LI nodes are active throughout all flight phases, including the ground operation. The expected data rates are low due to the low sampling rate. For instance, the sampling rate of the cabin temperature sensor is around 1 sample per second or less. The number of LI links is around 4150, where the average data rate per link ranges between 10 and 800 b/s, for a typical passenger aircraft [25]. Since most LI nodes are installed in hidden locations, nonline-of-sight (NLOS) propagation channel is dominant. Hence, WAIC transceivers of different compartments may operate at the same wireless channel if the metallic or conductive composite wall gives significant signal attenuation.

2) LO Class: The LO category includes low data rate monitoring applications, such as wheel position and speed sensors for control. Although the average data rate per link is below 10 kb/s, the sampling rate can be considerably different depending on applications. The monitoring application, such as door position, has a low sampling rate around several seconds to a minute, whereas control applications, such as wheel speed sensing need the anti-skid control at 2.5 ms [2]. Most LO applications fall into assurance levels A and B of Table I since they include safety-critical sensing and actuators, such as wheel speed, structural stress, ailerons, slats, and flaps. The number of LO links is around 400, where the average data rate per link ranges between 20 and 8 kb/s [25].

The LO applications do not gain the benefits of the signal attenuation since they operate outside the airframe in most cases. In Fig. 4, a significant number of LO transceivers are installed on exposed areas of the wing, tail, landing gear, and wheel wells [23]. For instance, when the flaps, ailerons, and spoilers are activated, many critical sensors and actuator transceivers of the flight control system are exposed at the wings and tail, as illustrated in Figs. 2 and 4.

3) HI Class: The flight deck communication, image, video, engine sensors, and avionics fieldbus belong to the HI class. The source traffic mainly consists of regular periodic traffic, such as high-resolution engine sensors and irregular traffic bursts, such as voice/image/video on-demand services. Engine sensors are located within engine nacelles, while most voice/image/video nodes are located in different compartments, such as the cabin, bays, and flight deck. Engine prognostic sensors are used to monitor various engine parameters for post-flight analysis on the ground. This data is not used for critical flight controls. The expected data rate demands of voice/image/video are in tens, hundreds, and thousands of kb/s, respectively. Furthermore, these HI applications typically require low latency (< 0.5 s) and low jitter (< 50 ms) to maintain the quality of on-demand services.

Most HI applications belong to assurance levels B and C of Table I. The number of HI links is around 125, where the expected data rate per link ranges between 12.5 kb/s and 1.6 Mb/s for a typical passenger aircraft. NLOS paths are the dominant wireless conditions except for some specific cases of the line-of-sight (LOS) paths within the cabin.

4) HO Class: The HO category includes structural health monitoring and active vibration control sensors. These sensors require a high data rate since they commonly require a high sampling rate with high-resolution measurements. For the rotorcraft, flight deck voice and video systems are categorized as outside due to its physical layout in contrast to the typical passenger aircraft [22].

Most HO applications fall into assurance levels B and C of Table I. The number of HO links is around 65, where the average data rate per link is between 45 kb/s and 1 Mb/s. Since LOS paths are the dominant wireless conditions in the HO category, WAIC transceivers outside the airframe could cause mutual interference.

V. General Challenges

As a general guideline, WAIC needs to be cost-efficient while providing comparable real-time and security performance to the current fieldbus technology of aircraft [32]. In this section, we classify the primary challenges into three categories, namely, operational requirements, design constraints, and monetary cost, as shown in Fig. 6. The operational requirement is the heart of the essential components to support the safety-critical flight control systems. Besides, WAIC systems are severely affected by design constraints, such as complex structure and monetary cost constraints, such as system integration and maintenance. Many design constraints, such as wireless channel, complex structure, and operation-dependent heterogeneous applications are unique challenges of WAICs while operational requirements and monetary cost are related to the ones of industrial networks [43], [44]. Moreover, the availability and deterministic requirements of WAICs are beyond what the current wireless networks of the industrial applications provide [31], [45]. Note that we will discuss the wireless channel as one of the significant technical challenges in Section VI.

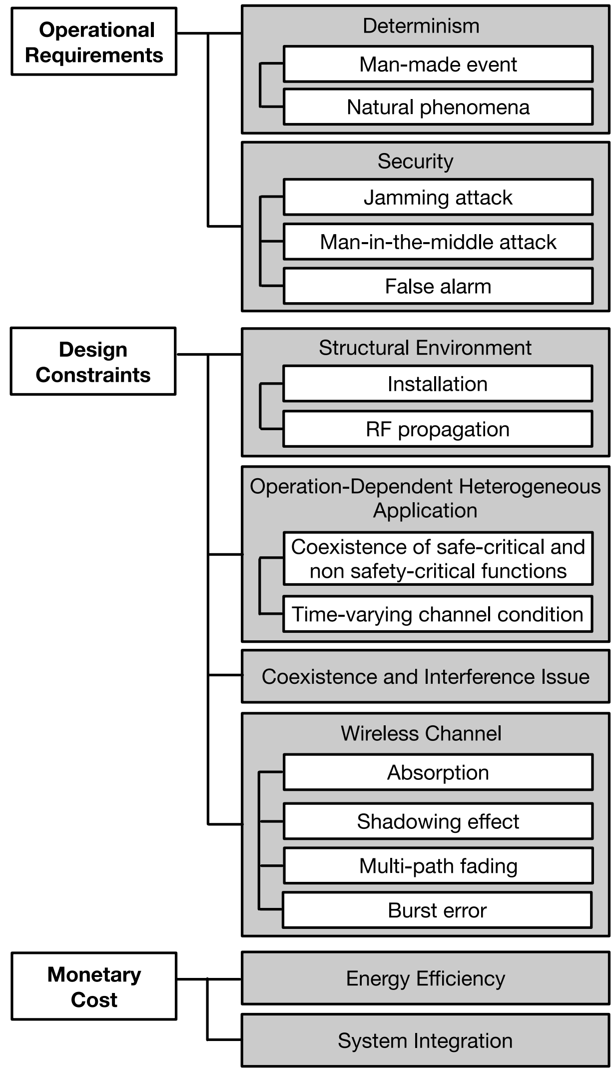

Fig. 6. Three primary challenges, namely, operational requirements, design constraints, and monetary cost and their detailed technical problems to design, analysis, and deployment of WAIC systems.

A. Determinism

WAIC systems must provide deterministic communications to ensure the safe operation of an aircraft. Note that the determinism implies that each packet of the network is delivered within a bounded interval. The deterministic performance essentially requires the extremely reliable and timely delivery of the network [46].

One of the major concerns to use wireless communication is the susceptibility against EMI since it can degrade or cause even malfunction of safety-critical avionic equipment. We define two main reasons as man-made event and natural phenomena. The man-made events include avionics noise, portable electronic devices, and interference from other aircraft, while natural phenomena involve lightning strikes, solar flares, and radiation. Furthermore, the wireless channel of the WAIC environment is still the most challenging task since it depends on many other factors, such as complex structures, operations, and natural disturbances.

The worst situation is that the pilot of the cockpit does not have a consistent view of the real state of the aircraft due to the uncertainties of the network performance. The real-time data must be delivered within a relatively short deadline for most control systems of aircraft. To guarantee the stability of closed-loop control systems, both the controller and actuator must receive the time-critical sensing data and feedback control signal, respectively, in a timely manner. The WAIC network generally includes a large number of sensing and actuating links, as shown in Table II. In particular, flight control systems consist of a large number of uplinks from sensors to measure speed and altitude with few downlinks to actuators, such as ailerons, slats, and flaps [2]. Uplink reliability is crucial to ensure successful packet transmission, such as sensor measurements from wireless node to backbone networks. Besides, downlink reliability must be guaranteed to deliver control or query packets from the backbone to the wireless nodes. In fact, the downlink to actuators turns out to be more important than one of the uplinks in most safety-critical control systems [47]. Hence, a network protocol should consider the reliability in both directions [48]–[50]. While the retransmission of data packet improves the reliability at the cost of the latency, outdated packets are generally not useful for control systems [35]. The delay jitter is especially difficult to compensate if the variation is large for control systems. The reliability and latency requirements of WAIC are more challenging than the ones of the traditional monitoring applications using industrial wireless networks [31], [51].

B. Security

Due to its broadcast nature, wireless networks are inherently subject to security threats. In WAIC systems, attacks can come both from onboard (passengers or other entities in the cabin) and outside the aircraft (ground or other aircraft). Differently from other WSN systems, data authentication and integrity are essential aspects to guarantee the safety-critical operations of aircraft.

Security attacks have been analyzed based on an adversary model in the context of wireless-enabled avionics [52]. The most relevant attacks for WAIC are summarized in the following.

1) *Jamming Attack:* Assets of an aircraft can be made unavailable, and operation can be disrupted by jamming the wireless medium. Although interference mitigation techniques reduce the impact of a jamming attack, prevention of this attack is not entirely possible, and the focus is instead on the early detection of such attacks.
2) *Man-in-the-Middle Attack:* To threaten aircraft safety or airline business, an adversary may attempt to corrupt, insert, or delete assets in the communication path among assets. An example is the manipulation of health diagnostics to prevent fault detection. In these cases, the attack is prevented by limiting physical access to assets by design. However, it needs to be combined with appropriate procedures for device provisioning and commissioning so that unauthorized access is prohibited.
3) *False Alarm:* Misleading alarms may not be a threat to aircraft security but can cause severe economic damages. An adversary can attempt to modify the configuration report to create misalignments between current and intended configurations. Data and configurations need to be protected against replay attacks, so that information cannot be spoofed and reused to alter the configuration.

C. Structural Environment

A WAIC system has variable RF propagation characteristics due to the harsh and complex structures of the aircraft with various materials. Furthermore, the installation of WAIC nodes is complicated since the structural integrity must be carefully maintained within physical space constraints. The basic aircraft structure can be made of either metal or composite materials, or some mixture of the two [53], [54]. Graphite epoxy has become a common option for modern commercial aircraft, though stainless steel or titanium is still used to endure the higher stress or heat for military aircraft. Note that most WAIC transceivers inside the airframe are installed in hidden locations or metal-enclosed areas.

Carbon-fibre and metal composite materials may result in significant multipath due to signal reflections [25], [33], [55]. Each wireless link might have high bit error rates due to multipath signals in metal-enclosed areas. Furthermore, the RF signals are substantially attenuated through absorption and shadowing effect due to some interior structures, passengers, baggage, and cargo [56], [57]. Although the metal composite material is extremely hard to propagate for radio waves, it gives potentials to efficiently share and reuse the communication resources among WAIC transceivers inside the airframe. If the RF isolation between different compartments is sufficient, multiple networks could operate at the same RF.

Outside WAIC transceivers usually experience lower path loss compared to applications inside the airframe. However, the safety-critical sensors and actuators installed outside the airframe are vulnerable to external interference from other aircraft or jamming attacks.

D. Operation-Dependent Heterogeneous Application

In contrast to the typical monitoring application of industrial WSNs, WAIC systems must support heterogeneous classes of functionalities, as we have discussed in Section IV. While some functions of aircraft are very safety-critical, most of them are less critical based on Tables I and II. WAIC must support both safety-critical and non safety-critical functionalities since non safety-critical ones can result in significant performance losses or damages to the aircraft in the long-term.

Most of the WAIC applications continuously operate during all flight phases, while some applications are only active for limited periods of time, depending on the aircraft operations. For instance, slats and flaps of Fig. 2 are mainly used for low-speed control during the critical operations of takeoffs and landings [23]. The WAIC systems must adapt their resource allocations based on these operational-dependent demands.

The aircraft operations could affect the radio propagation property since some parts of the aircraft change position. The reliable communication link between expanded landing gear sensors and gateway installed outside the airframe is guaranteed during landing and takeoff. However, the path loss significantly increases when the gears are closed during the in-flight mode.

E. Coexistence and Interference Issue

Since the frequency band between 4.2–4.4 GHz does not overlap with the ISM band, there is no serious concern with typical interference issues from existing wireless communication technologies. However, each aircraft still has to share the spectrum resources of 4.2–4.4 GHz with other aircraft. Since aircraft are widely spaced apart during in-flight mode to avoid the mid-air collision, the interference factor becomes negligible. Indeed, two aircraft are vertically separated by at least 300 m during the in-flight mode [58], [59].

However, the interference problem becomes severe when many aircraft are very closely located at the airport during parking or taxiing. On the ground, outside WAIC transceivers may cause substantial interference to other aircraft compared to inside ones. Many critical sensors and actuators outside the airframe are essentially vulnerable to co-channel interference and attacks since the airframe does not provide any protection. Hence, the interference between aircraft must be controlled to allow coexistence. Different diversity domains, such as time, frequency, and space are obvious countermeasures to handle interference [60]. However, some advanced techniques, such as interference cancellation and software-defined radios can be applied as well.

TABLE III
WIRELESS CHANNEL MODEL PARAMETERS OF LOG-DISTANCE PATH LOSS MODEL FOR EACH GROUP OF TEST PAIRS BETWEEN TRANSMITTERS AND RECEIVERS [25]

Group	Group name	Path loss exponent (n)	Description
A	Intra-Cabin & Intra-Flight Deck	2	Both TX and RX are in the same cabin area
B	Inter-Cabin	3.46	TX and RX are separated by cabin monuments
C	Inter-Cabin-to-Lower Lobe & Inter-Cabin-to-Flight Deck	2.49	TX and RX are separated by the main deck floor
D	Inter-Cabin-to-Exterior	2.12	TX and RX are separated by the fuselage
E	Inter-Cabin-to-Landing Gear & Inter-Lower-Lobe to Exterior	1.51	TX and RX are separated by the airframe
F	Inter-Exterior	2.31	Both TX and RX are exterior of the aircraft fuselage

F. Energy Efficiency

Low data rate applications may use battery-operated devices to further reduce the deployment and maintenance cost of WAICs. Note that all energy-constrained WAIC nodes must operate flawlessly during a long flight (below 20 h). Even though the true wireless device, operated on battery power, gives a great benefit for the WAIC operation, the energy resource must be carefully chosen [61]. For instance, some devices do not have any line power supply nearby, such as pneumatic actuators, whereas other nodes have access to it [22]. Furthermore, the aircraft operators may need to maintain various batteries of WAIC nodes to replace consumed batteries. Hence, the life-cycle cost of battery-operated wireless nodes can be more expensive compared to nodes that only communicate via the wireless medium.

G. System Integration

WAIC systems must not only meet the specific requirements of certification but also provide interoperability with existing avionics infrastructures. In Fig. 4, the gateway is one of the most critical points to efficiently integrate WAIC systems. However, since a small number of gateway vendors only propose proprietary solutions, the efficient integration to existing infrastructure is complicated. It is essential to standardize the WAIC integration into various avionics fieldbus to achieve simple deployment, low installation cost, and maintenance.

VI. WIRELESS CHANNEL AS KEY ASPECT

The effects of wireless propagation are the cornerstone to achieve high levels of reliability and security in a safety-critical aircraft environment. The Physical (PHY) and medium access control (MAC) layers of the WAIC system need to adapt their parameters dependent on the large-scale and small-scale fading effect of wireless channels. The WAIC environment is challenging as it has a highly complex aircraft structure with metallic ceilings, metallic joists, as well as moving parts affecting the scattering and reflection characteristics of the radio channel [2]. It typically contains a large number of devices generating wideband noise, such as motors and power supplies. Furthermore, the natural disturbances obviously affect the radio propagation property [62]–[65].

By considering the primary WAIC frequency, the wavelength inside the aircraft is smaller than other structural features like apertures and bulkheads. Hence, the aircraft structure significantly affects wave propagation by reflections or absorption. Since many aircraft environments are composed of metallic cavity-like structures, such as an empty fuselage or an avionics bay, they are highly resonant and low-loss [55]. The short-scale variation in the received signal inside the resonant environment can vary due to different paths with various attenuation [66]. Such cavities can cause severe multipath effects with time-varying frequency-selective channels from a communication perspective. Numerous reflections in an enclosed cavity result in much large delay than those in the design of typical wireless systems, such as IEEE 802.11 [67]. This section discusses existing ITU-R model, electromagnetic perspective research, and natural disturbance effects on the wireless channel in the context of the WAIC environment.

A. ITU-R Channel Model

The ITU-R report [25] provides the signal propagation model of a typical wide-body aircraft (an aircraft with two aisles) based on experimental measurements. By combining analytical and empirical schemes, a log-normal shadowing path loss model was used to model the wireless channel in various positions of the aircraft. Various sets of propagation measurements are used to develop the log-distance path model to capture the large-scale fading. Table III presents the set of test locations and path loss exponents [25]. These realistic link models can be used for simulation-based studies. The range of the path loss exponent is between 1.51 and 3.46. For group E, the calculated path loss exponent is less than the one of free space since the cabin acts as a resonant cavity. When test pairs are separated by deck floor or fuselage, the path loss exponents are between 2.12 and 2.49 due to a NLOS path. For group D, the cabin windows provide some near-LOS components. The largest path loss exponent 3.46 is obtained when both transmitter and receiver are separated by cabin monuments, such as lavatories and galleys, for group B.

Fig. 7 shows the path loss of all groups (A-F) of Table III and general cases of urban and rural areas of cellular communications [68] as a function of various distances between the transmitter and the receiver at 4.2 GHz. Note that we include the path loss of the general cellular communication as the reference to compare. We clearly observe the significant path loss of various test pairs with respect to one of the rural areas. In fact, group E gives the largest path loss since the transmitter and the receiver are isolated by the fuselage. To support the reliable communication, a large fading margin must be chosen to overcome a deep fade due to possibly moving carts and

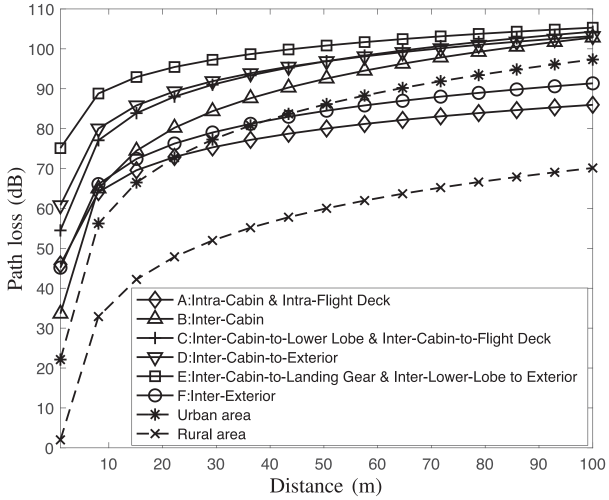

Fig. 7. Path loss as a function of different distances between transmitter and receiver with all groups (A–F) of Table III and urban and rural areas of general cellular communications [68].

passengers even in the cabin. Spread-spectrum modulation can also be used to improve the availability against deep fading.

The amount of interference between compartments mainly depends on the structure and material of bulkheads. Based on the channel measurements, it is possible to estimate the interference between compartments [25]. Then, we may reuse the channels while meeting the minimum signal-to-interference ratio for noninterfering regions. Since the outside WAIC environment generally has a good channel propagation property, the frequency reuse outside the airframe is not recommended on a single aircraft.

B. Electromagnetic Aspect

The electromagnetic perspective research is one of the interesting approaches to understand the complex effects of aircraft environments in wireless channels [55]. The reverberation chamber is used to characterize the wireless channel where the WAIC environment varies over space, frequency, and time [55], [69]. Note that the reverberation chamber is an electrically large cavity with a moveable stirrer. The stirrer of the chamber introduces randomness of the field reflections to capture the effects of the environment changes, including transmitter or receiver position changes.

The electromagnetic community uses the dimensionless and frequency-dependent metric called Quality (Q)-factor to quantify the energy storage capacity or resonant behavior of a cavity or circuit. From a communications perspective, the Q-factor is closely related to the mean access delay and the frequency fading properties since it heavily affects the strength of the indirect signals [55], [66]. A lower Q-factor generally makes the wireless channel more flat fading, rather than frequency-selective fading. It basically reduces the mean excess delay and the intersymbol interference of the channel. In [70], it is shown that the mean excess delay $\bar{\mu}$, for a large number of pulses, is proportional to the Q-factor, at a particular frequency ω_0 such that

$$\bar{\mu} \approx \frac{Q}{2\omega_0}. \tag{1}$$

Experimental studies have been conducted in various cavities, such as a large reverberation chamber ($4.7 \times 3.0 \times 2.37$ m), a small reverberation chamber ($0.6 \times 0.7 \times 0.8$ m) and a representative wing structure ($3.0 \times 1.0 \times 0.2$ m) [66]. The range of the Q-factor is between thousands to tens of thousands within various empty cavities. The Q-factor measurements are around 30 000–45 000 for a large chamber, 1000–4000 for a small chamber and a representative wing structure, and 700–1000 for several cavities inside a Tornado GR4 aircraft. As the cavity size increases, we typically obtain higher Q-factors. It is also possible to control the Q-factor by installing various radio absorbent material and a stirrer.

Wireless communication is reliable in the most practical environments where the Q-factor is below 1000. However, a reliability requirement is not guaranteed when the Q-factor is above 1000 since the delay spread becomes larger than a few microseconds [66]. Experimental results show that the direct-sequence spread spectrum modulation scheme of IEEE 802.15.4 effectively reduces the bit error rate for the lower Q-factor less than 1000 [55]. While they are generally reliable up to a Q-factor around 5000 in highly resonant environments, the results indicate potential bursty losses dependent on the transceiver positions, which is unsuitable for most WAIC applications. Furthermore, wireless communication is not feasible when the Q-factor is beyond 10 000 [33]. Frequency-selective fading is the main cause of communication failures in high Q-factor environments.

The experimental results show that the structural changes can significantly affect the channel behavior since the channel characteristics vary with the stirrer position changes in the reverberation chamber [55], [66]. Packet error rates (PERs) of IEEE 802.15.4 and IEEE 802.11 systems dramatically change between 0 to 100 percent, with 1mm movement of a structure in reverberation chamber tests. It means that the functional WAIC system might suddenly fail if a component moves. It is a critical issue in aircraft, where engines, turbulence, and landing induce significant vibrations. WAIC systems might have a sharp break, in which the system can fail to operate properly, rather than gradual performance degradation. The effect is less severe but still exists at lower Q-factors. The wireless network is not robust in a reverberant environment since its performance considerably depends on Q-factors and transceiver positions.

C. Natural Disturbance

WAIC system must guarantee the time-critical operation, even in the harsh environment, due to various pressure, temperature, humidity, and unexpected electrometeors and solar activities. While the wire shielding protects wired data transmission against outer distortions, wireless communication systems are inherently vulnerable to natural disturbances. Several natural disturbances possibly affect the signal propagation characteristics of the WAIC environment [62]–[64]. The most relevant natural disturbances of WAICs are atmospheric gases, hydrometeors, electrometeors, and solar activities [71]. Some ITU reports provide the signal attenuation model of various natural phenomena [62]–[65]. The model of [62] and [63]

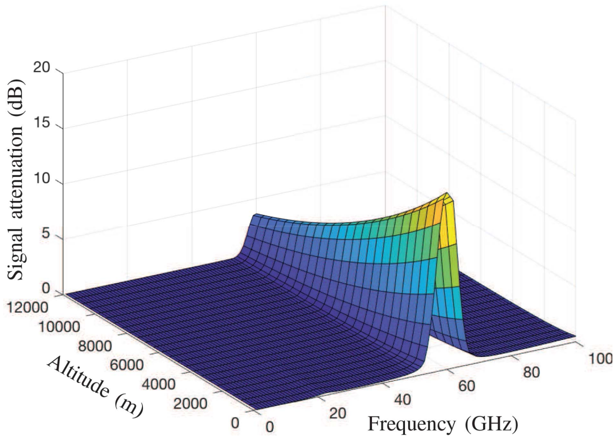

Fig. 8. Signal attenuation as a function of different operating frequencies 1–100 GHz and altitudes 0–12 000 m.

calculates the signal attenuation as a function of atmospheric gases for different altitudes. This signal attenuation model basically includes the pressure, temperature, and water vapor properties of a standard atmosphere. Besides, it is also possible to integrate varying signal degradation due to rain rate with altitude [64], [72]. Furthermore, the effect of the cloud and fog on the signal attenuation is modeled based on the statistical data of total columnar content [65].

To show the potential impact of natural disturbances, we implemented the signal attenuation model of the standard atmosphere [62], [63]. The model does not include the path loss effect to avoid the variations depending on the location of the node. The upper altitude boundary is set to 12 000 m based on the maximum operating altitude of A320 [73].

Fig. 8 shows the signal attenuation as a function of different transmission frequencies 1–100 GHz and altitudes 0-12 000 m. The main peak is around 57–60 GHz due to the resonance of Oxygen [63]. The received power is reduced by roughly 14 dB. The second peak is observed around 22 GHz, which corresponds to the resonance of water vapor. It is significantly lower than the main peak. Even though the attenuation gets higher as decreasing altitude due to the atmospheric gases, its effect below 10 GHz is negligible.

While the signal degradation due to atmospheric gases and hydrometeors is shown to be negligible on the primary spectrum 4.2–4.4 GHz of WAICs, both natural disturbances significantly degrade the signal propagation in the 60-GHz millimeter waveband of spectrum [71]. Hence, some new standards, such as IEEE 802.11ad [74] and IEEE 802.11ay [75] must carefully adapt their operations dependent on altitudes and weather conditions.

The natural disturbances of both the electrometeors and solar activities are extremely rare events compared to the entire operation time of flights. Although these natural disturbances affect the avionics systems, the effect analysis on the signal attenuation is not yet available.

VII. Candidate Wireless Solutions for WAIC

WAIC is an extremely broad research area covering various fields of embedded computing, sensing, and wireless communication technologies. From the early 21st century, the structural monitoring community has focused on developing various wireless sensor prototypes combined low-processing microcontroller coupled with analog-to-digital converters and energy harvesting modules to support the strong demands of the health monitoring applications of aircraft [92]–[95]. Wireless sensor platforms have gradually become mature through the rise of recent embedded hardware and sensing techniques. While it is not possible to provide a major literature review due to its recent subject, we still discuss some related works, specifically in the fly-by-wireless concept.

Developing a WAIC system from scratch is inefficient since many wireless standards are already in use in various commercial applications. Most wireless standards, such as IEEE 802.15.4, Bluetooth, and IEEE 802.11 currently work typically at 2.4 GHz and some at 5 GHz. Even if WAIC requires different frequency bands, such as the new frequency bands 4.2–4.4 GHz, existing systems can be adapted to this requirement by only replacing RF front ends and antennas while keeping the remaining sophisticated channel access techniques and system architecture. This strategy even helps the certification procedure since the aviation community can have better confidence in wireless networks being continually validated and used in various applications. Furthermore, a single technology is not suitable for all avionics systems due to conflicting demands between cost, power, and data rate. As a result, it is rational to combine a low power low data rate and high power high data rate wireless techniques.

We investigate the applicability of existing techniques to support the heterogeneous services of both low data rate and high data rate applications. For the low data rate applications, IEEE 802.15.4 is one of the strong candidates because it provides a sufficient range of communication, energy efficiency, scalability, and flexibility [96]. Most industrial low rate wireless standards focus on real-time communication based on the IEEE 802.15.4 PHY layer for large-scale monitoring of the noncritical process automation [31], [97]. Some experimental results show the applicability of the IEEE 802.15.4 PHY layer for harsh industrial environments [98]–[100]. In fact, many researchers have already used IEEE 802.15.4-based solutions for low data rate WAIC applications [28], [76], [78]. Although it is not originally designed for mission-critical applications, Bluetooth is also considered as a candidate technology for WAIC systems. The main reasons are the huge ecosystem of existing devices and the interoperability guaranteed by a full protocol stack certification [101]. There are recent efforts to apply cellular-based solutions, such as narrowband Internet of Things (NB-IoT) for low data rate WAIC systems [102]. Although appealing, these solutions are based on licensed operations and depend on the deployment of infrastructures by national telecommunication operators. In this survey, we consider technologies that can provide worldwide unlicensed operations.

Regarding high data rate applications, the IEEE 802.11 standard is a good basic technology since it offers high throughput with a number of possible modulation and coding options [67], [103]. WLAN can be used to deliver nontraditional variables, such as voice and video and to efficiently

TABLE IV
RESEARCH MATURITY LEVELS OF CANDIDATE WIRELESS TECHNIQUES, NAMELY, IEEE 802.15.4-BASED AND BLUETOOTH-BASED SOLUTIONS FOR LOW DATA RATE AND IEEE 802.11-BASED AND UWB-BASED SOLUTIONS FOR HIGH DATA RATE. BY CONSIDERING THE SPECIFIC CHALLENGE, EACH RESEARCH FIELD OF VARIOUS TECHNIQUES IS MARKED AS (⊕, ◯, −) FROM MOST TO LEAST MATURE ONE. WE DECIDE THE MATURITY LEVELS DEPENDING ON HOW LONG THE TECHNOLOGY HAS BEEN IN USE BASED ON WELL-ESTABLISHED SPECIFICATIONS AND WHETHER OR NOT THERE ARE PREVIOUS WORKS THAT ASSESS THEIR FEASIBILITY IN THE CONTEXT OF INDUSTRIAL AUTOMATION AND WAIC SYSTEMS

		Low Data Rate		High Data Rate	
		IEEE 802.15.4	Bluetooth	IEEE 802.11	UWB
Operational Requirements	Determinism	◯	−	−	⊕
	Security	◯	◯	◯	◯
Design Constraints	Structural Environment	−	−	−	−
	Operation-Dependent Heterogeneous Application	◯	−	◯	−
	Coexistence and Interference Issue	◯	◯	◯	−
	Wireless Channel	◯	−	−	◯
Monetary Cost	Energy Efficiency	⊕	⊕	−	◯
	System Integration	⊕	⊕	⊕	−

replace the existing high data rate fieldbus, such as AFDX [38] and AS6802 [104]. While enabling high data rate wireless communications was a significant achievement in the WLAN network, they do not guarantee any deterministic network performance in terms of availability, reliability, and latency. On the other hand, UWB is another potential candidate since it provides a high data rate with greater noise resistance, jamming resistance, multipath immunity, and penetration ability. However, it faces some fundamental technical problems, such as large bandwidth demands and interference.

This section discusses most related works of IEEE 802.15.4-based and Bluetooth-based solutions for low data rate applications and IEEE 802.11-based and UWB-based solutions for high data rate applications. We also present the spectrum division issue between low data rate and high data rate applications. Table IV presents the research maturity levels of candidate wireless standards along with the technical challenges. By considering the specific challenge, each research field of various standards is marked as (⊕, ◯, −) from most to least mature one. We decide the maturity levels depending on how long the technology has been in use based on well-established specifications and whether or not there are previous works that assess their feasibility in the context of industrial automation and WAIC systems. Table V compares existing related works in terms of various wireless techniques, technical challenges addressed, scenarios, and evaluation methods for WAIC. While each related work is marked as ⊕ if it explicitly considers the technical challenge to design or optimize the operations, we mark ◯ when it only reports the evaluation results of the standard corresponding to the technical challenge. The terms "Sim," "Ground," and "Flight" of the evaluation method mean the simulation, experimental ground test, and experimental flight test using aircraft, respectively.

A. Low Date Rate

This section discusses related works and technical issues of low power wireless standards for low data rate WAIC applications.

1) IEEE 802.15.4-Based Solution: The feasibility of adapting an existing IEEE 802.15.4 standard has been investigated in terms of reliability and data security for aerospace applications [76]. They conclude that the IEEE 802.15.4-compatible network is suitable for noncritical WAIC applications through a small scale demo point of view. However, the default CSMA MAC of IEEE 802.15.4 still suffers the high collision rate and unfairness issue [105]. Researchers develop various algorithms to improve the transmission efficiency of the CSMA protocol. Barcelo *et al.* [77] proposed a distributed algorithm to assign the beacon frames and the available channels for the cluster-tree topology to minimize the collision probability of the slotted CSMA protocol. The simulation setup includes 80 nodes uniformly deployed around the body and the wings of aircraft for health monitoring applications. The game theory is combined with CSMA protocol to improve packet loss, throughput, and fairness [106]. Krichen *et al.* [78] evaluated the feasibility of game-based CSMA protocol using the simulation models of the realistic sensor deployment in aircraft. To monitor vibration and detect flutter, 150 sensor nodes are deployed along aircraft wing of 40×10 m dimensions. Simulation results show that game-based CSMA outperforms the original CSMA protocol in terms of packet loss, delay, and throughput.

IEEE 802.15.4-based ZigBee is used to validate the suitability of the wireless-based measurement information systems [79], [80]. One of the interesting tests is performed during free-flight experiments by the LAK-20T glider [79]. Wireless sensors measure height and vertical speed where the measurement frequency of 2 Hz was set by considering the maximal aircraft flying speed, 300 km/h. The experiments collect 1400 measurement samples during 10-min free-flight. The experimental analysis shows a significant bursty loss of speed measurements during the free-flight caused by electromagnetic disturbances. These bursty losses are consistent with the experimental findings of previous electromagnetic researches [55], [66]. Notay and Safdar [80] simulated ZigBee protocol with hierarchical WSNs topology by using the OPNET simulator. They showed that packet loss, time delay, and throughput were closely related to the distance among nodes and the number of nodes.

Although several improved CSMA protocols have been proposed for aircraft monitoring systems [77], [78], they still face some performance limits because of the persistent collisions. The contention-free protocol, such as time-division multiple access (TDMA), generally provides a better deterministic performance, including latency, jitter, and reliability,

TABLE V

COMPARISON OF EXISTING RELATED WORKS IN TERMS OF VARIOUS WIRELESS TECHNIQUES, TECHNICAL CHALLENGES ADDRESSED, SCENARIOS, AND EVALUATION METHODS FOR WAIC. WHILE EACH RELATED WORK IS MARKED AS ⊕ IF IT EXPLICITLY CONSIDERS THE TECHNICAL CHALLENGE TO DESIGN OR OPTIMIZE THE OPERATIONS, WE MARK ○ WHEN IT ONLY REPORTS THE EVALUATION RESULTS OF THE STANDARD CORRESPONDING TO THE TECHNICAL CHALLENGE. THE TERMS "SIM," "GROUND," AND "FLIGHT" OF THE EVALUATION METHOD MEAN THE SIMULATION, EXPERIMENTAL GROUND TEST, AND EXPERIMENTAL FLIGHT TEST USING AIRCRAFT, RESPECTIVELY

	Classification				Technical Challenges								Scenario	Evaluation
	Low Data Rate		High Data Rate		Operational Requirements		Design Constraints				Monetary Cost			
	IEEE 802.15.4	Bluetooth	IEEE 802.11	UWB	Determinism	Security	Structural Environment	Operation-Dependent Heterogeneous Application	Coexistence and Interference Issue	Wireless Channel	Energy Efficiency	System Integration		
[76]	∨				○	○			○				1-hop	Sim
[77]	∨				⊕								multi-hop	Sim
[78]	∨				⊕		○				⊕		1-hop	Sim
[79]	∨				⊕		⊕					⊕	1-hop	Flight
[80]	∨				⊕		○					○	1-hop	Sim
[28] [81]	∨				○		⊕			⊕			1-hop	Flight
[82]	∨				○		○			○			multi-hop	Ground
[45]	∨				⊕						○		1-hop	Sim
[83]	∨				⊕						⊕		1-hop	Sim
[84]	∨				⊕						○		multi-hop	Sim
[85]	∨				⊕		○		○		⊕		multi-hop	Sim
[86]	∨				○	○					○	⊕	multi-hop	Ground
[87]		∨			⊕		⊕					⊕	1-hop	Ground
[88]		∨			○		⊕					⊕	1-hop	Ground
[10] [16] [17]			∨		○		⊕				○	⊕	1-hop	Flight
[89]			∨		⊕		⊕			⊕			1-hop	Ground
[90]				∨	○	○	○					⊕	1-hop	Sim
[56] [91]				∨	○		⊕				⊕	⊕	1-hop	Ground

than those using CSMA protocols. Besides, high-precision data synchronized acquisition is a crucial demand for efficient flight control and accurate damage localization [28].

Arms *et al.* [28], [81] developed an integrated structural health monitoring and reporting system by combining hard-wired and wireless sensors for use on Navy aircraft. The system includes a wireless sensor data aggregator and various wireless sensors to monitor strain gauges, accelerometers, and thermocouples. The IEEE 802.15.4 protocol is used to support a large number of wireless sensor nodes for the TDMA-based star topology. Experimental results show that the integrated network supports 100 strain sensing nodes with a 100 Hz sampling rate per node on a single channel [28]. When 16 channels in 2.4 GHz are enabled, the network scalability is extended to a maximum of 1600 strain sensing nodes with the same sampling rate. Furthermore, they install the integrated solution on a Sikorsky MH-60S [81]. Additionally, Blanckenstein *et al.* [107] proposed a centralized single-hop scheduling algorithm based on a simple TDMA protocol. The redundant access points (APs) exploit spatial diversity without automatic repeat request (ARQ)-based retransmissions. They present the experimental results of received signal strength indication (RSSI) and PER in an Airbus A330-300. The network consists of 500 sensor nodes grouped in three clusters, with two redundant APs per cluster to avoid a single point failure. The redundant AP considerably reduces the PER more than four times using a single AP.

Various industrial alliances, including the HART communication foundation [108], the International Society of Automation [109], and the Chinese Industrial Wireless Alliance [110] have established WirelessHART [108], ISA100.11a [109], and wireless networks for industrial automation-process automation (WIA-PA) [111] standards, respectively, to support the real-time communications [35], [112]. All these standards mainly rely on the TDMA-based MAC protocol while adopting the complete IEEE 802.15.4 PHY layer. WirelessHART and ISA 100.11a propose a new MAC layer combining TDMA and channel hopping techniques, whereas the WIA-PA standard renovates the existing IEEE 802.15.4 MAC layer. Main targeting applications of these standards are monitoring of process automation and equipment, which has relaxed requirements with respect to the ones of critical WAIC applications [45]. We refer to the papers [31], [112], [113] for extensive analysis and summary of industrial wireless standards for low data rate applications. The low cost and low power of these wireless standards make it appealing for low data rate WAIC applications [112], [113]. Some simulation studies are carried out to evaluate the performance of these standards: WirelessHART [49], [50], [114]–[116], ISA100.11a [51], [117]–[119], WIA-PA [120], [121] but they have different parameters or tools over various environments. Hence, it is hard to derive common conclusions due to the lack of quantitative performance comparison in a uniform simulation environment.

WirelessHART and ISA100.11a are discussed as an alternative solution to build a modular platform for WAIC systems since these standards overcome the essential shortcomings of IEEE 802.15.4 CSMA MAC [82]. In [45], we evaluate the feasibility of different industrial wireless networks, such as WirelessHART [108], IEEE 802.15.4e [122], and a wireless interface for sensors and actuator [123] to the flight safety requirements of Table I. While enabling real-time wireless communications is a significant achievement in these industrial communications, availability, and reliability requirements of the flight certification exceed what current networks can offer [45]. Hence, some improvements are still recommended for safety-critical WAIC applications.

While the time slot and the channel allocation are the most critical task for real-time WAIC applications, the industrial wireless standards do not define any specific scheduling algorithms [31], [112], [113]. Zhou and Jing [83] proposed star-cluster-based TDMA approaches where the length of the time slot is flexibly adjusted dependent on traffic demands. The synchronous message from the cluster head is used to adjust the clock of sensor nodes at a certain cycle. Simulations results show the significant advantages of the proposed TDMA protocol on packet loss, delay, and energy efficiency. Omiyi *et al.* [84] considered a network topology consisting of multiple linear sensor clusters terminated by actuators commonly adopted for active airflow control. Two interference aware convergecast scheduling algorithms, namely, serial line scheduling (SLS) and parallel line scheduling (PLS), are proposed to jointly minimize the delay and energy consumption of the TDMA-based linear multihop topology. The PLS maximizes the number of linear clusters activating in parallel, while SLS minimizes the time delay of data transmission by maximizing the number of assigned links per cluster. The proposed schemes mainly coordinate local communications in each cluster and arbitrate the interfering nodes of different clusters. Dai *et al.* [85] proposed TDMA-based hybrid line scheduling (HLS) by combining SLS, and PLS features to further improve the delay and energy efficiency. Simulation results show that HLS reduces the delay and energy consumption by 15% at a moderate number of sensor nodes of aircraft.

Sciancalepore *et al.* [86] proposed an advanced health monitoring platform called TLSensing integrating IoT open standards and the data collection process handled by the central system coordinator. TLSensing consists of a number of embedded devices, a central system coordinator that controls data acquisition processes through dedicated monitoring software, and a Web server application that collects data from the network and makes them available to the user for the health management system. The communication stack among the central system coordinator and constrained devices mainly relies on IEEE 802.15.4 PHY, IEEE 802.15.4e MAC, and IETF IPv6 routing protocol for low-power lossy networks. In order to guarantee confidentiality and authenticity services, messages are exchanged at the layer-2 by using security functionalities already defined in the IEEE 802.15.4 and IEEE 802.15.4e specifications.

2) Bluetooth-Based Solution: The primary usage of Bluetooth is the wireless connection between a mobile phone and a headset. Bluetooth low energy (BLE) [101], released in 2010 as part of Bluetooth 4 specification, has been standardized to expand the ecosystem of Bluetooth to the IoTs. The focus is primarily in the smart home sector, but it could possibly impact the industrial applications because of the huge ecosystem of compatible devices (e.g., smartphones) [124]. A tradeoff between reliability, delay, and sensor lifetime is analyzed depending on the data transmission mode [125]. Rondón *et al.* [126] analyzed the BLE performance for time-critical industrial applications, relying on various retransmission schemes. Although high reliability and low latency constraints can be achieved separately, the simultaneous fulfillment of all requirements for flight safety is not achieved.

As a fly-by-wireless unmanned aerial vehicle (UAV) platform, Carvalhal *et al.* [87] designed and develop a distributed data acquisition system using a single Bluetooth piconet. The piconet consists of seven nodes with one master and six slaves where the master node is placed at the fuselage body, and six slaves are deployed over the wing, fuselage body, tail, and nose. The master node serves as the network and flight controller and onboard data logger. Several performance evaluation tests are conducted to analyze the suitability of the developed system using a proprietary embedded virtual machine produced by connectBlue [127]. From the slave to master communications, the system prototype could support a sampling rate of up to 200 Hz for each slave without any significant performance degradation in terms of packet loss, delay, and throughput. For the master to slave communications, while the delay is low for less than 4 slaves, its value significantly increases for more than five slaves due to the limitations of the virtual machine. Coelho *et al.* [88] also developed a similarly flexible and distributed architecture where processing is distributed on embedded sensors using the Bluetooth standard. They demonstrate the feasibility of the Bluetooth piconet for a small distributed avionics system in the UAV with 4.8×2.9 m dimension. However, the network consists of few sensors with very low data rates than a real aircraft due to the fundamental limits of the Bluetooth scalability.

There are some rather complex issues that must be addressed to create the WAIC network using Bluetooth masters and slaves. The main issue is how to schedule and coordinate all the concurrent connections with a general topology since the standard does not specify it. The standard also does not mandate how many concurrent connections shall be supported while there are practical limitations. For instance, the popular Nordic nRF51822 chipset supports only 8 connections [128].

Bluetooth has recently introduced mesh networking capabilities, namely, Bluetooth Mesh Profile, based on the connectionless approach to provide more flexible and scalable networks with guaranteed interoperability [129]. However, some devices need to continuously scan the advertising channels, which significantly degrade the energy efficiency. Furthermore, the network is more vulnerable to advertising channel congestion or jamming attacks.

B. High Data Rate

This section discusses related works and technical issues of IEEE 802.11-based and UWB-based solutions for the high data rate WAIC applications.

1) IEEE 802.11-Based Solution: WLAN is an excellent network infrastructure for high data rate WAIC applications with readily available off-the-shelf products and technical maturity [11], [130], [131]. Note that IEEE 802.11 is a set of PHY and MAC specifications for WLAN communications. However, the IEEE 802.11 technology is not yet capable of the real-time transmission and high data rate demands of WAIC applications due to some fundamental limitations on reliability, latency, and throughput [11], [132]. The general WLAN standards, such as IEEE 802.11a/b/g are widely used for various applications, but they do not assure any deterministic reliability, latency, and throughput performance for time-critical applications [132], [133]. The main reason is that the default contention-based distributed coordination function (DCF) scheme does not inherently provide any deterministic performance.

IEEE 802.11 provides the optional contention-free point coordination function (PCF) [133]. When centralized PCF is activated, the wireless communication is organized with temporal windows called superframes. PCF is the preferable solution since the network resources can be deterministically assigned to ensure the transmission of data within a specific period. However, PCF still fails to satisfy the strict real-time requirements of critical industrial applications since the transmission periods are in the range of several hundred milliseconds [134]. To deal with this problem, the industrial wireless LAN (IWLAN) technology extends the IEEE 802.11 standard using industrial PCF protocol to meet the real-time and redundancy requirements [11], [135]. In this protocol, a master uses a polling scheme to manage the sequence of transmissions. However, the throughput of IWLAN is low since the protocol assigns each time slot to all associated nodes.

To serve different Quality of Service (QoS) requirements of various applications, the IEEE 802.11e standard introduces a new adaptive framework called hybrid coordination function (HCF) [136]. HCF modifies the original DCF and PCF to support both new QoS features of time-critical applications and non-QoS features of traditional applications within a network. For instance, IEEE 802.11e is used to provide low latency communication for the factory automation system [130].

Although WLAN is one of the strong candidates, there are only a few researches explicitly targeting high data rate WAIC applications. The space shuttle of NASA uses IEEE 802.11-based wireless sensors for health monitoring [16], [17]. Although all detailed information is not available, the wireless LAN-based technique achieves the data rate on the system from tens of kb to a 2 Mb. Besides, spread-spectrum techniques are used for combating the multipath effects.

We use the IEEE 802.11-based software-defined radio platform and design monopole antennas to make them compliant with the 4.2–4.4 GHz frequency band of WAIC. To characterize the small-scale fading effects, field tests are conducted to measure the received power distribution in the light aircraft [89]. In contrast to the extensive channel measurements of the large-scale fading [25], the small-scale fading effect is not well established for aircraft. The communication link is observed between several points, such as cockpit, engine room, rear room, and wing spots. Note that different compartment environments are filled with electronic devices and mechanic components in practice. The root-mean-square delay between measured points for NLOS transmission is between 272–328 ns. The power delay profile (PDP) shows that LOS signal path is dominant for most cases since the distance between transmitter and receiver is relatively short, less than 2 m. This result is consistent with the *Q*-factor effect of the Tornado GR4 aircraft in the electromagnetic point of view [66].

2) UWB-Based Solution: Rather than operating within a limited frequency band, such as the 2.4 GHz ISM band, UWB spreads information over a large bandwidth ($>$ 500 MHz) while maintaining the very low spectrum density such that its effects are negligible to existing equipment. Besides, it provides high robustness against possible interference and jamming. Dang *et al.* [90] proposed a hybrid architecture combining ECMA-368-based UWB and switched Ethernet to reduce communication delay and electromagnetic susceptibility and increase scalability. ECMA-368 is a standard working in a large frequency band from 3.1 to 10.6 GHz for a short-range operation. This standard supports a data rate of 110, 200, and 480 Mb/s in a range of 10, 6, and 2 m, respectively. The performance evaluation considers the realistic geographical locations in avionics bays since many time-critical subsystems are concentrated at the head of the aircraft. The proposed architecture consists of three clusters with two clusters in the main bay and one cluster in the upper bay where the frequency band is assigned to each cluster to avoid interference. Since the area of each avionics bay is less than a 6-m diameter circle, the achieved rate is about 200 Mb/s.

In a mockup of a small passenger cabin, Neuhold *et al.* [56] evaluated the reliability of the off-the-shelf UWB network. Sensor nodes with up to 17 nodes send their data to one of several APs where each AP is connected to the application server. They measure the RSSI and PER to analyze the path loss model of LOS propagation and the shadowing effect of the obstructed links. By the least-square fitting, the average reception power over distance gives a path loss exponent around 2 in the hallway and head panel deployment. They also evaluate packet loss between nodes and APs when eight people move in the cabin as realistic case studies. Note that moving passengers cause the small-scale fading. If passengers disrupt links between senders and receivers, it results in packet loss since it degrades the received power. Furthermore, the reception power drastically drops if the signal propagates through an occupied seat. These observations are comparable with the signal attenuation effect due to the human body [57].

Although previous works [56], [90] consider UWB as a potential candidate for WAIC solutions, UWB has some fundamental issues in terms of bandwidth, interference, market support, and regulation. Since the UWB technology spreads the transmitting information over a large bandwidth, it does not comply with the primary spectrum band of WAICs. WAIC has the bandwidth restriction to 200 MHz in 4.2–4.4 GHz. Even if the IEEE 802.15.4-2011 UWB standard is possibly comparable with the main spectrum band of WAIC, the performance will be significantly lower than the expected one due to the limited use of the bandwidth.

Owing to the potential UWB interference on GPS, the Federal Communications Commission has a conservative approach in the UWB regulation [137]. Note that GPS is the most critical component of all flight phases. The potential interference with UWB is a problem due to the extremely weak GPS signal around −130 dBm [138], [139]. An extensive study is needed to quantify the impact of aggregated interference when many UWB nodes are spatially deployed around the GPS receiver in aircraft. Furthermore, the UWB interference still remains a concern to the existing onboard equipment. Besides, market support is weak relative to other existing technologies, such as IEEE 802.15.4, Bluetooth, and IEEE 802.11 standards. Some countries (e.g., Australia) even restrict UWB operation onboard an aircraft.

C. Coexistence and Spectrum Division

Low data rate applications can be considered separately from high data rate applications because the bandwidth and latency requirements are significantly different. ITU-R mainly considers application demands and communication constraints to derive the spectrum requirements for heterogeneous WAIC applications [25]. While the application demands include sensor types, number of nodes, average and peak data rate, and operation period, the communication constraints are the modulation efficiency, channelization overhead, protocol overhead, and multiple aircraft. Based on the extensive analysis of technical characteristics of WAIC, the spectrum requirements per aircraft are about 35 and 53 MHz for low data rate and high data rate applications, respectively, [25]. Since the WAIC system utilizes the 4.2–4.4 GHz as the main spectrum [21], it is possible to divide the entire spectrum into two segments for low and high data rate applications. In this way, we eliminate the coexistence issue between low and high data rate applications and simplify the design of entire WAIC systems [140]. For instance, WAIC may allocate 80 and 120 MHz out of the total 200-MHz band to low and high data rate applications based on the ratio of the spectrum requirements [25]. In fact, the IEEE 802.15.4 standard uses the 83.5 MHz band by subdividing into 16 channels, where each one has a 2-MHz bandwidth with a 5-MHz channel separation in the 2.4-GHz band [96]. By considering IEEE 802.15.4, we obtain around 15 channels using 80 MHz for the low data rate applications. In a similar way, we have around 5-6 channels, each with a bandwidth of 20 MHz over 120 MHz for the high data rate applications. Hence, it is possible to resolve the coexistence issue between IEEE 802.15.4 and IEEE 802.11 frameworks by dividing the main spectrum.

VIII. Open Challenges and Future Research Directions

Despite the significant advancement of current wireless networks, no existing wireless techniques can be used exclusively to meet the safety requirements of WAICs, as discussed in Section VII. Most existing works typically focus on non safety-critical applications, such as health monitoring systems, with a small number of nodes. There are several technical challenging problems to be solved out to support the large scale critical applications of WAIC systems.

A. Machine Learning for Parameter Management

To support the time-critical operations, WAICs must carefully optimize a large number of parameters among different layers of the network. Mathematical input/output models have been typically used to select the set of parameters of communication systems. However, the interactions among the layers and practical limits, such as interference and circuit nonlinearities, are hard to model by simple expressions of adequate accuracy [141]. Furthermore, the complexity of recent wireless systems can seriously increase as the result of multiple input multiple output antennas, wide spectrum usage, natural disturbing factors, and various algorithms at different layers [75], [103], [142]. The accurate prediction of reliability and delay is extremely challenging since these metrics depend on the wireless channel realization and the assigned network resource. Hence, the traditional adaptive resource management does not perform well in practical WAIC systems.

Deep learning (DL) technique is an effective tool to solve several technical challenges of WAIC networks with large-scale topology and complex channel conditions. Some recent papers provide an extensive survey of the potential applications of DL models at different layers of wireless networks [143]–[145]. One of the most promising tools is the online machine learning approach to select the communication parameters based on the real-time measurements of performance metrics, such as reliability and delay [144]. Online learning not only captures changes in the system model based on the data set but also learn the hidden features of system operation details. WAICs can provide several sets of network parameters where each set is associated with various performance metrics, such as reliability and delay. Thus, adaptive resource management based on DL models is achieved by predicting the reliability and delay for each parameter set before the packet transmission [146]. Furthermore, reinforcement learning models are recently tied with many DL frameworks for resource allocation, routing, and network optimization since the communication system continuously interacts with the environment, including the time-varying channels [145], [147].

However, DL models are mostly used as black-box models without formal guarantees due to their nonlinear and large-scale nature. As a consequence, DL models are vulnerable to input uncertainties or adversarial attacks [148]. Such disruptions can be either of an adversarial nature [149], or merely compression and cropping [150]. These fundamental drawbacks limit the adoption of DL models for safety-critical applications [151]–[153]. Recently, many types of research have been conducted for developing tools to measure or improve the robustness of DL models. Most works focus on specific adversarial attacks and attempt to harden the network, such as crafting hard-to-classify examples [154]–[156]. Although these methods are scalable and work well in practice, they still suffer from false negatives. Safety-critical WAIC systems require provable robustness against any bounded variations of the input signal. One of the most reasonable solutions is to use the data-driven DL approach as a complementary solution to traditional design techniques based on mathematical models of the wireless network design [157]. The mathematical models can greatly reduce the amount of real data to implement data-driven DL approaches.

B. Machine Learning for Fault-Detection and Diagnosis

WAIC must provide efficient fault-detection and diagnosis mechanisms to meet the high criticality level and the required probability of failure [6], [32], [158]. However, the major avionics systems still have the manual and template-driven scheme for the fault-detection and diagnosis [6], [159]. While the DL method could potentially improve the fault-detection and diagnosis performance, the inference and training still require significant computational resources to run in practice [160]. The recent integration of DL and edge computing essentially solves the problem of the high-computation and low-latency requirements of the data-driven fault-detection and diagnosis [44]. Edge computing is a distributed computing scheme in which information processing based on DL models is locally performed to improve the response time, bandwidth efficiency, and scalability. However, distributing the logic into various network nodes introduces new challenges [161].

C. Machine Learning for Effective Security

Concerning the network-level security, WAIC systems can benefit greatly from current DL frameworks. Given a rather predictable and static flow of information available in WAIC, with a limited number of traffic classes, the system can easily learn traffic patterns from measurements and generalize it to possible future anomalies or identify patterns that deviate from normal behavior. It reduces the cost of predetermined rules to distinguish intrusions [145]. Traffic flow inference can be achieved at different layers, starting from exploring MAC-layer parameters (interpacket arrival, packet size, etc.) to higher layer information with more intrinsic features.

Moving further from the classification of security threats, DL is then greatly useful for intrusion detection and anti-jamming policy in WAIC systems. For example, DL with auto-encoder offers 98% accuracy in classifying four types of traffic in IEEE 802.11 networks, including flooding and impersonation traffic [162]. Besides, DL with a restricted Boltzmann machine has been proven effective with 99.1% accuracy rate on intrusive behavior in a WSN-based network for safety-critical applications [163]. The reinforcement learning is also applied to derive a frequency-space anti-jamming communication policy without knowing the jamming and interference nodes and the wireless channel model [164].

D. Realistic Wireless Channel

One of the major difficulties of WAIC research is the lack of realistic channel models under practical operating conditions. Most existing measurements for indoor wireless channels have been focused on office environments with frequency bands different to 4.2–4.4 GHz [165], [166]. Only a few measurement campaigns are conducted on aircraft environments with their specifications [25], [56], [89]. In particular, the small-scale fading effect is not well established for aircraft with respect to some channel measurements of the large-scale fading [25], [56]. Few field tests are only conducted to measure the received power distribution in the light aircraft [89].

Further measurement campaigns are essential for developing simulators and accurate models of wireless channels in real WAIC settings. We suggest two representative campaigns to collect standard-independent measurements, such as the PDP using spectrum and network analyzers and standard-dependent measurements, such as RSSI and PER using real chipsets and software-defined radio. PDP measurements can be performed regardless of specific wireless standards for the given frequency band. In contrast, the protocol parameters of standards, such as modulation type, data rate, and packet size affect RSSI and PER measurements. Measuring PDP enables us to estimate the fading and pathloss characteristics of the channel and show the dependency of the received impulse response to the type of wireless environment encountered and the transmitter/receiver positions. Moreover, root-mean-square delay spread and coherence bandwidth can be estimated from the measured impulse responses. It is possible to make an even more general characterization of the WAIC environments from these two groups of measuring techniques.

For WAIC systems, it is crucial to perform long term measurement campaigns that cover all phases of operation of an aircraft to capture potential bursty losses and operational-dependent uncertainties since several factors, such as engines, turbulence, and landing will incur the significant vibrations. Since WAIC environments include many moving objects during a long flight, the channel conditions change between LOS and NLOS between the transmitter and the receiver. The channel parameters can change suddenly and remain stable for a short or long period.

E. Link Adaptation

Critical WAIC applications require extremely high reliable and low latency transmissions to meet the safety requirements [36]. IEEE 802.15.4, Bluetooth, and IEEE 802.11 standards are generally configured to balance the tradeoff between throughput, latency, and energy efficiency. However, the typical target PER 0.01 and 0.1 of both IEEE 802.15.4 and IEEE 802.11 standards, respectively, do not fulfill the flight safety requirements [45]. For instance, the possible target PER of critical actuating link is around 2×10^{-4} based on the required target bit error rate of 10^{-6} for 224 b/packet in flight control systems [10].

The forward error correction (FEC) scheme is one of the most suitable techniques to achieve high reliability and low latency [167], [168]. It is particularly suitable for time-critical sensing data and control command transmissions of closed-loop controls since the general ARQ scheme does not meet the high reliability and low delay demands [169], [170]. However, the overhead is still applied even if there is no error in the link [171]. The default standard of IEEE 802.15.4 does not include FEC, while many IEEE 802.11 standards typically use turbo or low-density parity-check codes to improve the throughput.

The FEC options need to be optimized since many critical WAIC applications typically have a short data payload up to a few hundred bits. Several channel codes, including convolution codes, polar codes, turbo codes, and low-density parity-check codes, are analyzed dependent on the block error rate, throughput, and complexity using practical decoders for ultrareliable low latency communications [172].

F. Joint Design of Control and Communication

A majority of current embedded wireless systems have largely focused on noncritical monitoring applications. When we apply the current common approach to critical closed-loop control applications, we face several technical challenges, including tight deadlines and safety requirements, as discussed in Section V. We must rethink the communication architectures and protocols to maintain the control stability and performance even in the presence of disturbances to WAICs.

Wireless networked control systems (WNCSs) is a key approach for bridging the gap between control and communication aspects [35]. WNCS consists of spatially distributed sensors, actuators, and controllers that communicate through wireless networks rather than traditional wired fieldbus connections. In the most common approach of WNCSs, sensor nodes transmit the measurements of the plant state; controllers then compute the control signal based on the received plant state and send it to the actuators in order to affect the physical plant. Guaranteeing stability and safety of closed-loop control is an extremely challenging task mainly due to network uncertainties, such as packet losses, delays, and node faults.

In practice, the dedicated controller typically imposes a set of requirements in terms of reliability, delay, or update deadline of the network [35], [173], [174]. However, since the assignment of network resources and routes is a generally static setup, it requires global reorganization with large overheads to adapt dependent on packet losses, delays, and faults. Besides, the control configurations must be recomputed dependent on the network changes [35], [175]. Moreover, physical node-level programming is one of the fundamental reasons for the poor robustness of WNCSs [176].

The possible research direction is to apply the distributed computation paradigm to the WNCS design based on WAICs. The entire network itself serves as a controller by spreading the computation of the control algorithm instead of assigning a specific node as the controller node. In other words, the control functions can be decoupled from the physical node. In the presence of unexpected network changes, it could efficiently migrate the control tasks to the most reliable set of candidates for maintaining the stability and safety of aircraft. Furthermore, even if a single sensor is unavailable due to link losses, faults, or attacks, the nodes should cooperate to compute the control signal without interruptions.

G. Energy Harvesting and Energy Delivery Through Metal

Energy harvesting techniques harmoniously compensate for the limitation of batteries since aircraft generate consistent vibration and heat when they are operating [177]. The periodic battery replacement is impractical for energy-constrained devices within sealed containers of aircraft. For instance, the vibration of the aircraft environment is a good energy source that can be effectively harvested either by electromagnetic induction mechanism or piezoelectric energy conversion mechanism [178], [179]. By using moving magnets or coils, vibrational magnetic generators can produce energy in the range of microwatts to milliwatt depending on the microelectromechanical system. Piezoelectric energy harvesting devices also generate the output power density of 100 and 330 μW/cm^3 [180], [181]. In space shuttles, energy harvesting technology has been successfully applied to reduce the maintenance costs of wireless sensors [17].

The conducting nature of the aircraft prevents the RF signal propagation because of the metal skin effect [25], [89]. Furthermore, to maintain structural integrity, it is often not desirable to drill holes between bulkheads of aircraft when installing the WAIC nodes. Piezoelectrics, inductive coupling, and electromagnetic acoustic transducer is another interesting technique to communicate and deliver power through a metal wall [182]. Using inductive coupling, a power transfer efficiency is around 4% through 20-mm thick stainless steel. Furthermore, the underlying physics of sheet may be used to produce surface waves at metal-air interfaces for power and data transmission [183].

H. System Integration

While WAIC needs to be connected to central control systems through high data rate buses, it does not explicitly define the specific type of backbone networks [2]. As avionics systems progress, there is a strong desire to move to more Ethernet-based networks in order to support the high data rate demand while reducing the development cost [29], [32]. Hence, Ethernet-based fieldbus networks, such as AFDX [38] and Time-Triggered Ethernet [104] are good candidates since many industrial wireless standards are also IP-compatible.

Since there are significant differences between wireless networks and these avionics data buses at both the PHY and MAC layers, a gateway must integrate the data bus network interface, acting as a wireless network AP [184].

1) IEEE 802.15.4, Bluetooth, and IEEE 802.11 Adaptation: IETF 6LoWPAN [185] and IETF 6LoBTLE [186] provide an IP interface for IEEE 802.15.4 and Bluetooth, respectively. The adaptation layer allows the direct communication of IEEE 802.15.4 and Bluetooth devices to other IP devices. IETF 6LoWPAN and IETF 6LoBTLE include two main functions: 1) the packet size adaptation and 2) the address translation between these networks. IEEE 802.15.4 (resp. Bluetooth) nodes still have a short 16-b (resp. 48 b) address instead of a long IPv6 address (128 b) to simplify the operation and save the bandwidth. In WAIC, the gateway could convert the address between a short address of low data rate networks and a 128-b address of the IP-based backbone network.

IEEE 802.11 uses a unique 48-b address as the IEEE 802 standard family. Since IEEE 802.3 Ethernet and IEEE 802.11 use the same logical link control as defined by IEEE 802.2, IEEE 802.11 and Ethernet-based fieldbus networks are relatively simple to integrate.

2) Wireless Backbone Networks: It is possible to replace fieldbus backbone to emerging high data rate WLAN standards. The wireless backbone is particularly attractive to further reduce the weight of small UAVs since the weight contribution of the backbone is significantly greater than that of sensing and actuating connections [22]. Furthermore, the safety requirement of small unmanned aircraft is relatively lower than the one of manned aircraft [187].

IEEE 802.11ad [74] and IEEE 802.11ay [75] support the WLAN communications in the 60-GHz spectrum. Since the maximum transmission rate of IEEE 802.11ay (resp. IEEE 802.11ad) is 40 Gb/s (resp. 7 Gb/s), this technology is a good candidate as the backbone WAIC network. Note that IEEE 802.11ay archives much higher transmit rates than the one of IEEE 802.11ax due to the larger bandwidth. However, both IEEE 802.11ad and IEEE 802.11ay standards must carefully adapt their parameters depending on the atmospheric gases and hydrometeors. Furthermore, these standards are hard to penetrate any types of walls in the 60 GHz spectrum [188].

IX. Conclusion

WAICs bring significant advantages to improve efficiency and flexibility while reducing the costs of installation and maintenance over traditional fieldbus networks of aircraft. In this article, we have surveyed opportunities, technical challenges, and existing works to develop and deploy the emerging WAICs for aircraft. We described the safety level of various critical operations and the current state of the art of the frameworks in terms of system classifications based on data rate demands and transceiver installation locations. We then discussed the major technical challenges for realizing the envisioned aircraft applications and particularly raised the issues related to the wireless channel and the network design. The WAIC basically needs to be cost-efficient while providing comparable real-time performance to current fieldbus over harsh and complex aircraft environments. Furthermore, existing wireless techniques were briefly discussed to investigate the feasibility of current solutions to support critical heterogeneous applications. Among the candidate technologies, IEEE 802.15.4 and Bluetooth have been considered for the low data rate applications, IEEE 802.11 and UWB for high data rate applications. Finally, we highlighted future research directions by considering the recent development of machine learning, edge computing, and joint design of control and communication.

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