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Radio Altimeter Interference Mitigation in Wireless Avionics Intra-Communication Networks

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***Abstract*—On-board commercial passenger aircraft Wireless Sensor Networks (WSNs) are anticipated to be used for implementing machine-to-machine communication also referred to as Wireless Avionics Intra-Communications (WAIC). These systems enable safety-related wireless avionics and aim to reduce electrical wiring harness contributing by 5% of the total weight of an aircraft. The globally harmonized frequency band designated for WAIC usage is shared with aeronautical Radio Altimeters (RAs). Literature lacks consideration of the impact of on-board RAs on WAIC systems; thus, we close this gap by performing a detailed study and propose two mitigation techniques based on channel hopping. Our simulations show that harmful RA signals infer doubled to tripled delays as well as packet error rates up to 90% when WAIC systems use the frequency band without applying appropriate techniques for increasing communication robustness. With the developed mitigation techniques, we show delays can be kept at levels comparable to non-interfered performance while increasing the usable spectrum by 50% simultaneously. Our evaluations show that the presented mitigation techniques enable reliable usage of WAIC systems in commercial aircraft allowing increased spectrum usage.**

I. INTRODUCTION

The civil aviation industry is currently developing standards for Wireless Avionics Intra-Communications (WAIC). WAIC addresses safety-related machine-to-machine communications on board commercial passenger aircraft. These systems are intended to provide highly reliable short-range radio communication between two or more avionic systems and respective sub-systems on board the same aircraft.

A crucial factor in this regard is the availability of a globally harmonized radio frequency band with predictable characteristics in terms of signal propagation and coexistence with other users operating in the band. The World Radio Conference 2015 [1] decided on a new allocation in the 4200 MHz to 4400 MHz band dedicated for the use of WAIC.

This frequency band is also used by aeronautical Radio Altimeters (RAs) operating on board the same but also different aircraft. Thus, a shared use of the frequency band by RAs and WAIC systems succumb the risk of harmful mutual interference, e.g. increased packet error rate. Future aviation standards must protect the operation of already fielded RA and ensure that WAIC systems are robust against RA interference.

This paper contributes to the development of these standards by providing an assessment of the interference impact of RAs on WAIC systems with co-frequency operation on board the same aircraft. We propose a specific medium access design for WAIC systems oriented to industrial Wireless Sensor Network (WSN) standards which was implemented in an OMNeT++ [2] simulation model. Furthermore, we reflect the interference environment by building a discrete simulation model of the RA. We assess the expected interference impact, provide two methods for mitigation and evaluate their performance. Our evaluations show, that the dedicated frequency band can be used efficiently by WAIC systems without risking harmful impact of RAs by applying the presented mitigation techniques.

The remainder of the paper is organized as follows: Sect. II introduces International Telecommunication Union (ITU) guidelines on WAIC systems and prior work on the topic of RA interference. Sect. III introduces the demands on WAIC systems, proposes a suitable medium access scheme and describes our OMNeT++ simulation model. The characteristics of RAs are presented in Sect. IV together with the description of our channel and discrete simulation model. The analysis of the expected interference impact is given in Sect. V together with two mitigation techniques. Sect. VI discusses the simulation results and provides a comparison of the mitigation technique performance.

II. GUIDELINES AND PRIOR WORK

The civil aviation industry is developing WAIC systems with the aim to reduce electrical wiring harness on board passenger aircraft. Electrical wiring harness contributes up to 5% of the total weight of an aircraft [3]. In consequence, the introduction of safety-related wireless machine-to-machine communications will increase fuel efficiency and reduce the carbon footprint of aircraft. Furthermore, it will ease the installation, reconfiguration and maintenance costs of avionic systems. Thus, WAIC systems are expected to lower production, maintenance and operational costs of the new generation of modern passenger aircraft.

Reference architectures of WAIC systems adopting parts of the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard and possible applications are described in [3]. Example applications are structural health monitoring, cabin temperature monitoring and cabin illumination. Thus, WAIC systems should support the demands of sensors as well as actuators by providing reliable communication with low delays. Since the number of WAIC-equipped aircraft is

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expected to grow, the system design should be spectrum-efficient to retain flexibility, e.g. [3] proposes to limit the spectrum used by WAIC systems per aircraft to $35\,\mathrm{MHz}$.

The $4200\,\mathrm{MHz}$ to $4400\,\mathrm{MHz}$ band allocated for the operation of WAIC is also used by aeronautical RAs. The purpose of a RA is to provide accurate and reliable measurements of the minimum distance to the Earth surface. RAs operate in all phases of flight including those where the aircraft is located on ground. Technical characteristics of RAs in operation today can be found in [4].

Both WAIC and RAs are essential components of aeronautical safety-of-life systems. Therefore, future aviation standards must ensure that WAIC systems and RAs operating co-frequency are able to coexist [1].

Studies contained in [5] assessing the potential of harmful mutual interference between WAIC systems and RAs show that coexistence of systems operated on board different aircraft is possible.

Analyses performed in [6] show that the operation of Frequency Modulated Continuous Wave (FMCW) RAs, which are predominantly used in civil aviation, is not affected by interference of WAIC transmissions, when the signal power observed at the RA receive antenna remains below $-50\,\mathrm{dBm}$. Interference Path Loss (IPL) measurements between the output of a RA antenna and several locations inside the aircraft fuselage are evaluated in [7]. The evaluation concluded that the minimum IPL from the RA antennas to WAIC systems operated on board the same aircraft is $85\,\mathrm{dB}$. Above results indicate that low-power WAIC systems are unlikely to cause harmful interference on RAs operated on board the same aircraft. Thus, the WAIC systems considered in this paper use low transmit power levels generating an Equivalent Isotropically Radiated Power (EIRP) below $10\,\mathrm{dBm}$.

The susceptibility of WAIC systems to interference caused by RA operated on board the same aircraft, however, has not been analyzed.

III. BACKGROUND AND CONCEPT OF WAIC SIMULATION

First, we present relevant ITU guidelines for WAIC systems and introduce common industrial WSN medium access techniques. Second, our design concept of WAIC systems is discussed.

A. Scope and Architecture of WAIC Systems

Many applications benefiting from the use of WAIC are installed inside the aircraft fuselage and relate to control tasks. These systems typically have a hierarchical architecture including a central controller and produce relatively low amounts of data. Existing standards for low data rate wireless communication systems in industrial automation, process control and related applications offer sufficient communication performance for the majority of these applications. Since WAIC systems operate in productive environments, we choose a leading industry standard for WSNs, ISA100.11a [8], for the WAIC design concept considered for the interference analysis.

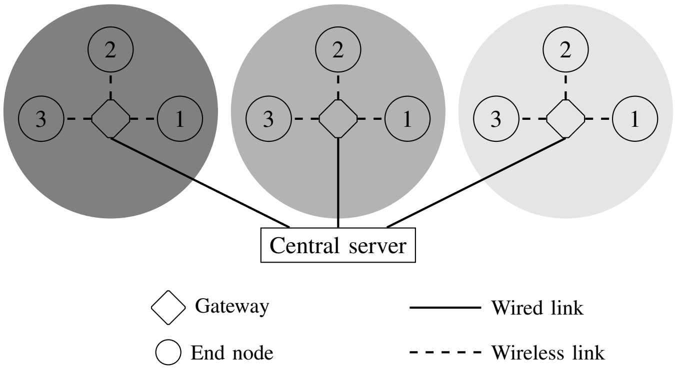


Fig. 1. WAIC network components forming a multi-star topology.

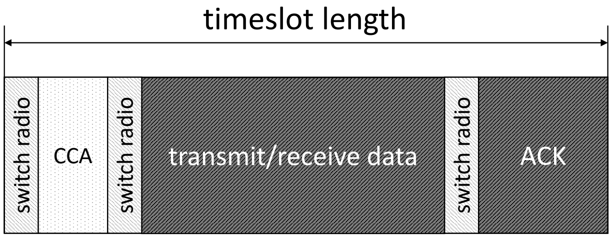


Fig. 2. Timeslot with optional CCA, data packet and acknowledgment.

As depicted in Fig. 1, WAIC systems consist of gateways and end nodes. Gateways provide the wireless interface to the traditional avionics network and establish a wireless connection to the end nodes, which offer the physical part of the WAIC system, e.g. temperature sensing or controlling window shades. Each gateway has a wired connection to central aircraft systems; thus, the resulting network has a multi-star topology. End nodes and gateways are located inside or outside the fuselage, e.g. at the wingtips. In systems located inside the fuselage, multiple end nodes are connected to one mutual gateway via short wireless communication paths. Since their distance from each other is small, low bit error rates due to high Signal-to-Noise Ratio (SNR) are expected.

Communication will either occur from gateway to end node, called downlink, or from end node to gateway, referred to as uplink; thus, direct communication between end nodes is not considered.

B. Medium Access

Multiple sensor network standards aiming at professional industrial automation, e.g. ISA100.11a [8], IEEE 802.15.4e as an extension of [9] and WirelessHART [10] rely on Time Division Multiple Access (TDMA).

Transmissions in TDMA-based sensor networks are bounded to timeslots. In the ISA100.11a standard, the timeslot length can be freely chosen between $3\,\mathrm{ms}$ and $20\,\mathrm{ms}$. As depicted in Fig. 2, a timeslot provides time to exchange data and its corresponding acknowledgment, switch radio multiple times and an optional Clear Channel Assessment (CCA) phase to detect ongoing transmissions on the medium. The radio switching times for transceivers compatible to ISA100.11a [8] must be shorter than $200\,\mu s$. A repeating set of timeslots forms a superframe. The communication behavior of the network and additional control parameters are always defined for one superframe. To increase robustness against interference, ISA100.11a offers the ability to use channel hopping. Scheduling or resource assignment is not part of the standard and has to be implemented by the system integrator. Taking WAIC architecture and industrial medium access techniques into account, we present our design concept in the following.

C. Designing a WAIC System

The scheduler used for this design concept assigns a fixed number of timeslots within one superframe for network traffic load, according to application demands, but also assigns dedicated retransmission timeslots. The assignment is fixed and performed by an external scheduler with linear binary scheduling as presented in [11] according to the need of the served applications in the WAIC system, e.g. delay requirements or data rate. Without external interference, error-free transmission can be assumed, since regular timeslots are exclusive. As interference is expected, retransmissions on the MAC layer are supported to compensate a certain amount of transmission failures. Allocated retransmission timeslots are shared among all nodes of a WAIC system. Thus, retransmitted packets may collide. Therefore, we implement a backoff scheme, which randomly chooses one of the following five retransmission slots to avoid subsequent packet collisions. To ensure new data is transmitted with low delay, we allow out-of-order-delivery for packets.

In accordance to the IEEE 802.15.4 PHY layer specifications, we choose a channel bandwidth B_W of $5\,\mathrm{MHz}$, which allows the system to use 40 channels in the $4200\,\mathrm{MHz}$ to $4400\,\mathrm{MHz}$ band.

Our design concept of WAIC systems adapts existing interference robustness techniques by using channel hopping, which already showed good performance in [12]. Based on the interference environment, we can adjust the channel hopping patterns of our simulation model to reduce harmful impact. The selected sequence is assigned to one superframe and is thus repeated during the simulation. By a central server, as shown in Fig. 1, gateways may be assigned different hopping sequences, which affects its connected end nodes as well. This allows separation of different parts of the system in frequency domain.

Since we use a central scheduling, CCA is not needed to detect interference between nodes of the same system in exclusive slots, but can be activated for detecting other sources of interference or to avoid collisions in retransmission timeslots.

Successful communications in WAIC systems contain the correct data packet reception and the corresponding acknowledgment. To decide on correct reception of packets, we use the SINR, defined as:

$$\mathrm{SINR} = \frac{S}{I+N}. \tag{1}$$

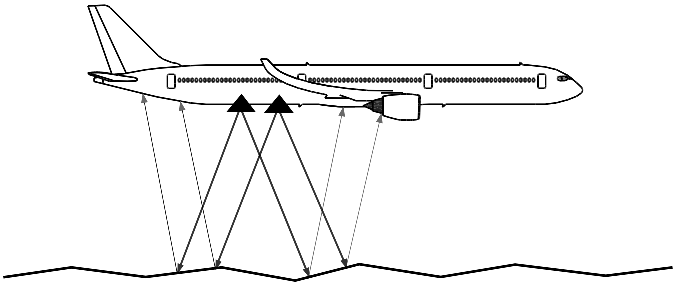


Fig. 3. RA position indicated by filled triangles; RA operation principle: height information is obtained from frequency difference between sent and received signal; reflected signal impacts WAIC nodes.

Here, S denotes the received signal power of the WAIC signal, N the present background noise and I the received power of the interference source, in our scenario predominantly FMCW RAs. Since S and I scale with distance d, the distance between gateway and end node influences communication as well as distance between RA and gateway or end node, respectively. The received signal power of WAIC signals is calculated by the transmission power and is attenuated with log-distance path loss model [13]

$$\mathrm{PL} = \mathrm{PL}_{\text{ref}} + 10\gamma \log_{10} \frac{d}{d_{\text{ref}}} \tag{2}$$

with path loss exponent $\gamma = 2.6$ and $\mathrm{PL}_{\text{ref}} = 45\,\mathrm{dB}$ for $d_{\text{ref}} = 1\,\mathrm{m}$.

An increasing I due to presence of the RA signal on the channel leads to an increasing Bit Error Rate (BER) and following packet loss. The dependency between SNR and BER can be found in [9] assuming that interference of RA signals is noise-like.

Our design concept is implemented in the discrete-event simulator OMNeT++. The PHY layer, propagation models and message classes are based on the MiXiM framework [14] and are adapted to support 40 channels with different center frequencies.

IV. RADIO ALTIMETER

The commonly used FMCW RAs use the echo signal of the Earth surface to determine the minimum distance below the aircraft. They are essential parts of aircraft's safety-of-life systems and their usage is mandatory for commercial passenger aircraft. The principle of RA is depicted in Fig. 3. First, we briefly present the principles of aeronautical RA. Second we show the IPL and waveform model in our simulation.

A. FMCW Principle

As depicted in Fig. 4, FMCW RAs use continuously and linearly in- or decreasing frequency ramps, also referred to as up- or down-chirps. An RA signal is described by its center frequency f_c, chirp bandwidth B_S and the chirp duration T_C. The instantaneous signal bandwidth is $1\,\mathrm{Hz}$.

Signals of RAs installed on board the same aircraft are not time synchronized and are typically offset in center frequency

TABLE I
TECHNICAL CHARACTERISTICS OF RAS

Parameter	Type A1	Type A2
Center frequency f_c	$4300\,\mathrm{MHz}$	$4300\,\mathrm{MHz}$
Transmit power P_R	$0.6\,\mathrm{W}$	$1\,\mathrm{W}$
Chirp bandwidth B_S	$104\,\mathrm{MHz}$	$132.8\,\mathrm{MHz}$
Chirp duration T_C	$19.6\,\mathrm{ms}$	$6.67\,\mathrm{ms}$
Interference time T_I	$0.94\,\mathrm{ms}$	$0.22\,\mathrm{ms}$

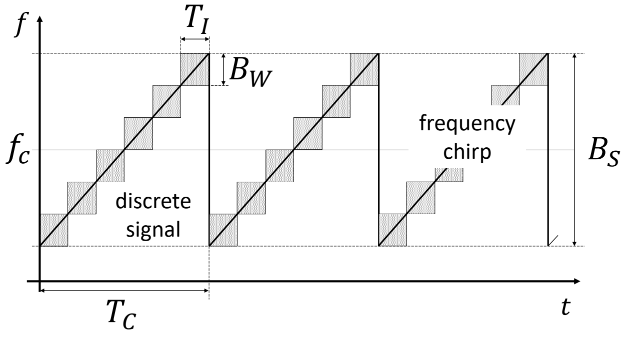


Fig. 4. Transmit chirp of FMCW RA and discretized signal of RA as implemented OMNeT++ simulation.

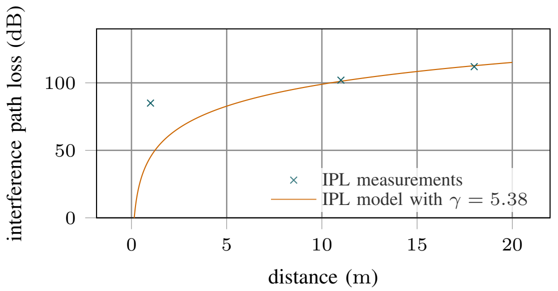


Fig. 5. Measured mean IPL and fitted curve for $\gamma = 5.38$. IPL is shown dependent on distance between RA and WAIC receiver.

f_c by $5\,\mathrm{MHz}$. RA transmit antennas are separated in space (usually $3\,\mathrm{m}$) and oriented towards ground. An extract of RA types defined in [4] is depicted in Table I, e.g. type A2, which occupies over 60% of the spectrum every $6.67\,\mathrm{ms}$.

B. Modeling IPL

We use the presented measurements in [7] to calculate the interference path loss based on Eq. (2). When the aircraft is located on the runway, the interference signal is attenuated in mean by $\mathrm{PL}_{\mathrm{ref}} = 85\,\mathrm{dB}$ at $d_{\mathrm{ref}} = 1\,\mathrm{m}$ horizontal distance, by $102\,\mathrm{dB}$ at $11\,\mathrm{m}$ distance and by $112\,\mathrm{dB}$ at $18\,\mathrm{m}$ distance. Our curve fitting yields a path loss exponent of $\gamma = 5.38$. The conservative fitting underrates the path loss within small distances; thus, the presented impact of the interferer is overrated. The resulting interference path loss dependent on the distance d between receiver and RA is depicted in Fig. 5.

C. Modeling RA Waveform and Interference

Within our simulations, the interference level for SINR is computed as shown in Eq. (1) and Eq. (2), with respect to the transmission power P_R of RA signals attenuated with the path loss exponent γ and the distance between WAIC receiver and RA. Interference at WAIC receivers occurs when the RA instantaneous frequency resides inside the channel filter bandwidth of the receiving system node. Assuming that the receive filter bandwidth is approximately $5\,\mathrm{MHz}$, as specified in IEEE 802.15.4, the interference time T_I describing the time a RA signal is present on a WAIC channel with channel bandwidth B_W, is calculated by the following formula:

$$T_I = \frac{B_W}{B_S} \times T_C. \tag{3}$$

Thus, chirp bandwidth B_S and chirp duration T_C directly influence the interference time. Our OMNeT++ simulation model of the RA is configured to emit multiple packets of length T_I during the chirp duration T_C with a transmission power P_R as given in Table I. Figure 4 depicts this principle in more detail.

V. MITIGATION TECHNIQUES

A. Share Ratio

The RA frequency chirp is expected to have a large influence on the WAIC system. With further distribution of WAIC systems, on the same aircraft or on other aircraft, the bandwidth demand will increase; thus, omitting WAIC transmissions from B_S reduces flexibility and extendability significantly.

Consequently, the main goal of mitigation techniques is to increase the usable spectrum in the designated frequency band. Figure 6 shows, that only a distinct number of channels is blocked by the RA. Since hopping patterns of our WAIC model can be freely chosen, different interference-free sequences with different numbers of channels inside the RA spectrum can be found. Thus, a metric is introduced to assess the benefit of a specific sequence. The goal is to use as many channels inside B_S as possible without an increase in error rates. Thus, the share ratio

$$SR = \frac{N_{\mathrm{I}}}{N_{\mathrm{U}}} \in [0, 1] \tag{4}$$

relates the number N_{I} of used channels inside the bandwidth of the RA to the overall number N_{U} of used channels in one sequence. E.g. a sequence containing three channels in total but only one channel is located inside B_S yields $SR = 0.33$. Combined with delays and loss rates, SR allows performance assessment of mitigation techniques, since it indicates the spectrum usage of one single WAIC system.

Thus, we propose channel hopping as one interference mitigation method to avoid the RA signal effectively.

B. Channel Hopping

The usage of TDMA together with channel hopping as presented in Sect. III-C allows for an interference mitigation technique based on adaption to the time-frequency behavior

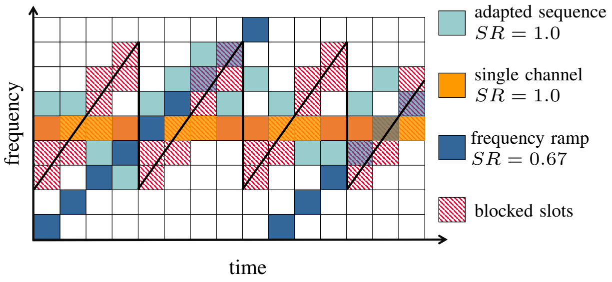


Fig. 6. Examples of used channel hopping sequences. Each sequence has different numbers of used channels inside B_S; thus, they have a different share ratio. Note that SR changes w.r.t. to chirp bandwidth B_S.

of the RA. A distinct sequence is assigned to one superframe and is known to all nodes. If a transmission on one channel fails, a retransmission in a next timeslot on another channel is more likely to be successful assuming different qualities.

Nevertheless, the used frequency channels should be adapted to the present interference environment. The usage of channel hopping enables us to assign communication resources in two dimensions: time and frequency. We argue that a highly accurate way to avoid interference completely is channel hopping. Since the time-frequency behavior of the RA is known, channel hopping allows to change the channel if presence of the RA signal is expected in the used timeslot. Since aircraft require static reliability levels for certification purposes, no dynamic reconfiguration of hopping sequences is performed during runtime.

Assuming that WAIC systems can be synchronized to RA signals, we create an adapted hopping sequence with the following algorithm.

Algorithm 1 Channel Selection

```
$k \leftarrow$ first slot in superframe
while $k$ in superframe do
    determine blocked channels by RA
    remove from list of available channels
    randomly select one of remaining channels
    add selected channel to hopping pattern $P$
    $k \leftarrow k + 1$                    ▷ proceed with next timeslot
end while
Use pattern $P$ for WAIC system
```

The sequence of selected channels forms the hopping sequence adapted to the signal of the RA. Figure 6 depicts the idea of the three simulated sequences. The single channel sequence is very likely to experience high interference, since the RA signal is present in many slots. The frequency ramp, which is required as one standard pattern in [8], uses all available channels in increasing order. The adapted sequence is the result of the developed algorithm, which uses the knowledge about the RA signal.

While the algorithm is able to increase the number of usable channels by ten for RA type A1, the benefit of using adapted sequences for RA type A2 is low: since the RA signal repeats rapidly, nearly no free channels are selected in between. This leads to share ratios of $SR = 0.43$ for RA type A1 and only $SR = 0.03$ for type A2.

Furthermore, the usage of adapted sequences requires time synchronization between WAIC and RA. While synchronization between WAIC nodes is obtainable, synchronization to the measurement signal of the RA is not simply achievable in practice. Since synchronization is easily achievable in simulations, we evaluate the synchronized and the unsynchronized case to show the potential performance. Note that in our channel hopping investigations, the whole WAIC system uses the same hopping sequence.

C. Spatial Mitigation

The investigation on channel hopping shows the weakness of this mitigation technique. Because the measurements of [7] and the model presented in Sect. IV-B show a high interference path loss, we propose the enhanced spatial mitigation technique. WAIC nodes in the rear section of aircraft are more likely to suffer from RA interference than nodes in the front.

Channel hopping sequences can be assigned on a per-gateway basis: end nodes connected to the same mutual gateway use the same sequence. This allows to assign frequencies outside the RA chirp bandwidth to devices located closely to the RA, while devices located at the front of the fuselage transmit on channels inside the chirp bandwidth. The sequences can be assigned dependent on SINR or on loss rate of the gateway.

In contrast to previous mitigation techniques, the spatial mitigation technique requires different gateways to use different channels. Thus, each gateway gets a distinct sequence with a known share ratio. The assignment of hopping sequences to gateway groups (gateways and their connected end nodes) dependent on their loss rate is called scheme. Different assignments result in different schemes. Overall, this leads to an increased average share ratio $\overline{SR}$ in the system without the need for synchronization between RA and WAIC, while loss rates are expected to stay at lower levels.

Excluding gateways 5 to 8 and their associated end nodes as depicted in Fig. 7 from the blocked channels, results in a relatively low share ratio of $\overline{SR} = 0.5$ but promises low loss rates. Other groups in the system operate within the bandwidth of the RA which results in scheme S1. Scheme S3 reaches a high share ratio of $\overline{SR} = 0.71$ by assigning sequences with high share ratio to gateways with partial interference and by assigning sequences with relatively low share ratio to the highly interfered gateways. An even higher $\overline{SR}$ is achieved with scheme S4 when only the two most disturbed gateways are excluded from channels inside B_S. Table II summarizes the schemes with respect to the present group interference level.

VI. EVALUATION

Using our simulation model, we compare the impact in case of unadapted frequency usage to adapted channel hopping and spatial mitigation performance. First, we introduce a realistic scenario for WAIC usage and used simulation parameters.

TABLE II
SCHEMES AND AVERAGE SHARE RATIO OF THE SYSTEM

	group interference level			
	no	partial	high	$\overline{SR}$
S1	1	0	0	0.5
S2	1	0.167	0	0.54
S3	1	0.667	0.167	0.71
S4	1	1	0	0.75

Second, the high impact of RA signal interference is shown if single channel, standard hopping sequences and CCA are used. Third, we show the performance of the developed mitigation techniques, which can reliably reduce or even resolve the harmful impact.

Three main metrics are used to evaluate the impact of the interference and the performance of our mitigation techniques. The share ratio allows to classify the efficiency of frequency usage. The goal is to obtain share ratio values up to one while keeping the two other metrics, delay and loss rate, on low levels. The delay is defined as the difference between creation time of the packet on the application layer of the sender and reception time on the receivers application layer. This also includes queuing delays on sender side.

The transmitted packets in a timeslot are data packet and the corresponding acknowledgment. Loss of either data packet or acknowledgment leads to retransmission. Hence, the loss rate L for node i is defined as:

$$L_i = \frac{\text{lost transmissions}_i}{\text{attempted transmissions}_i} \,. \tag{5}$$

Note that lost transmissions include losses due to RA interference but also collisions between WAIC nodes in shared retransmission timeslots.

A. Scenario

The WAIC system topology considered for the evaluation is depicted in Fig. 7 and represents a realistic distribution of nodes inside the aircraft's fuselage. Eight gateways are evenly distributed over the length of the cylindrical fuselage above the hand luggage spaces. Each gateway is connected to four end nodes, located at passengers reading lights and window controls; thus, the system contains 40 nodes in total. In the depicted topology, wireless transmission links range from $2\,\mathrm{m}$ to $5\,\mathrm{m}$. In addition to WAIC nodes, three RAs are located in the rear section of the aircraft. We evaluate interference of two different RA types as described in Table I.

The system nodes follow a predefined schedule obtained from the scheduler of [11]: they use two thirds of the superframe to serve their traffic and can use the remaining third for retransmissions. The resulting mean usage of timeslots in one superframe is 38%. The inter-arrival time of the exponentially distributed packet generation has a mean value of $1.28\,\mathrm{s}$ and up- and downlink follow the same pattern.

The timeslot duration of $5\,\mathrm{ms}$ in combination with a data rate of $250\,\mathrm{kbit/s}$ and radio switching times allows for a packet payload of $64\,\mathrm{B}$ as stated in [3]. The CCA duration is $128\,\mathrm{\mu s}$ but turned off if not mentioned otherwise. Since the exponentially distributed traffic and the random time offset between WAIC system and RAs leads to variation of the results, all simulations are repeated 48 times with different seeds to increase confidence. Note that the figures do not show confidence intervals, since they are too small to be visible. Further simulation parameters can be obtained from Table III. All simulations use the same parameters; thus, the different mitigation techniques can be compared directly.

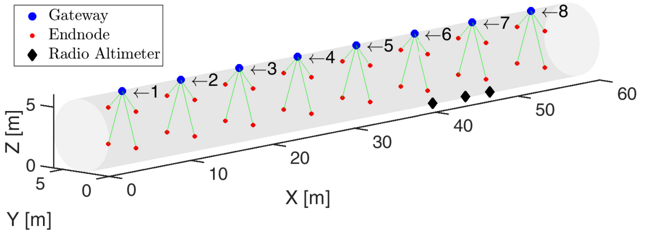


Fig. 7. Simulated WAIC system topology inside cylindrical fuselage.

TABLE III
SIMULATION PARAMETERS

CCA duration	$128\,\mathrm{\mu s}$
Radio switching time	$38\,\mathrm{\mu s}$
Data rate	$250\,\mathrm{kbit/s}$
Packet payload	$64\,\mathrm{B}$
RA path loss exponent (γ)	5.38
WAIC path loss exponent (γ)	2.6
WAIC transmission power (P_{TX})	$10\,\mathrm{mW}$
WAIC receiver sensitivity	$-84\,\mathrm{dBm}$
Thermal noise	$-114\,\mathrm{dBm}$

B. Single Channel and Standard Performance

Without knowledge of the RA, the proposed WAIC concept relies on mandatory standard patterns of ISA100.11a or on single channel transmission. To underline the need for mitigation techniques, Fig. 8 shows the average loss rate of the whole WAIC system. Dependent on the RA, average loss rates of up to 23% for single channel use in the interfered frequency band can be expected. The performance of the frequency ramp is slightly better since it also contains undistorted channels.

High loss rates result in significantly higher delays, c.f. Fig. 9. For comparison, the undistorted case by transmitting on a single channel outside the interfered spectrum is also shown. Even with RA type A1, mean delay is nearly doubled; interference of type A2 leads to ten times higher mean delay.

The usage of CCA generally has little impact. The loss rate is slightly decreased by 1% at the cost of an increasing mean delay of roughly $50\,\mathrm{ms}$. Since RA and WAIC are not synchronized, the RA signal might only interfere with the rear part of the timeslot. Thus, a packet may be lost although CCA is active which explains the marginal performance gain.

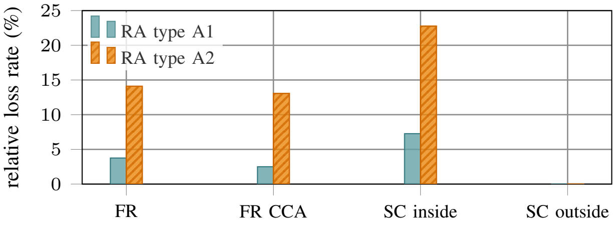


Fig. 8. Loss rates for different hopping patterns as average of all nodes in the WAIC system; usage of CCA has minor influence, usage of single channel inside B_S results in high loss rates.

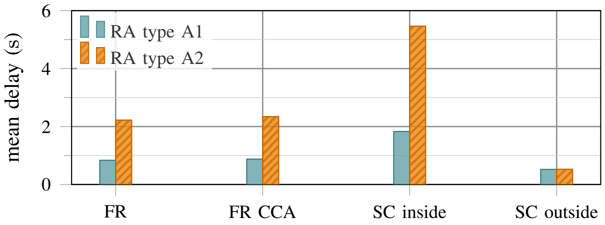


Fig. 9. Mean end-to-end delay on application layer; usage of CCA increases delay slightly, usage of single channel inside B_S results in three to ten times higher delay.

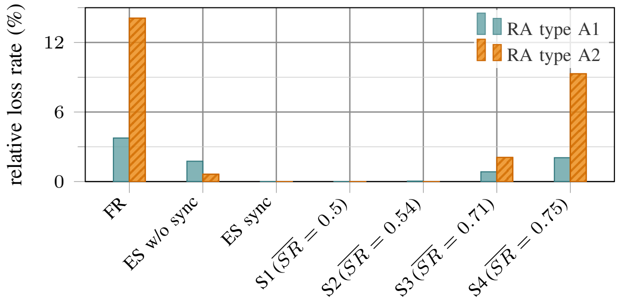


Fig. 10. Loss rates for enhanced hopping sequences with and without synchronization to RA and spatial mitigation for different average share ratios; loss rates significantly reduced compared to frequency ramp.

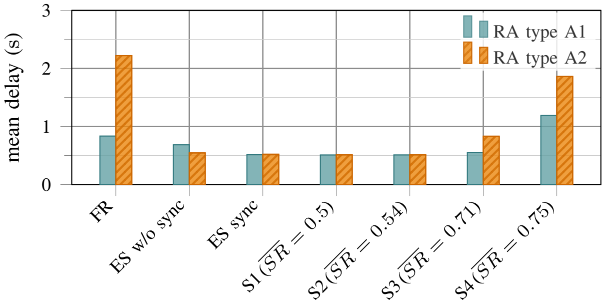


Fig. 11. Mean end-to-end delay on application layer; with synchronization, delay similar to undistorted case; spatial mitigation schemes S1 and S2 provide delays similar to undistorted system.

C. Channel Hopping Performance

Adapting to the RA signal by using enhanced hopping sequences is a promising approach. As depicted in Fig. 10, this technique works satisfyingly if synchronization to the RA can be obtained. If synchronization is not possible, the performance is primarily determined by the number of used channels inside the RA spectrum by the sequence. Even with RA type A1, which provides a share ratio of $SR = 0.43$, the loss rate can only be reduced by 54% compared to the frequency ramp. With RA type A2, loss rates can be reduced by 94% compared to single channel use but the gain due to the low share ratio of $SR = 0.03$ is negligible.

The mean delay, depicted in Fig. 11, shows similar behavior. When synchronization to the RA signal can be obtained, the results are similar to interference-free transmission. Without synchronization, the share ratio is low and low delays are the result of the rare use of channels inside the RA spectrum. Thus, the algorithm provides no real gain in reality, if no synchronization to the RA signal can be obtained.

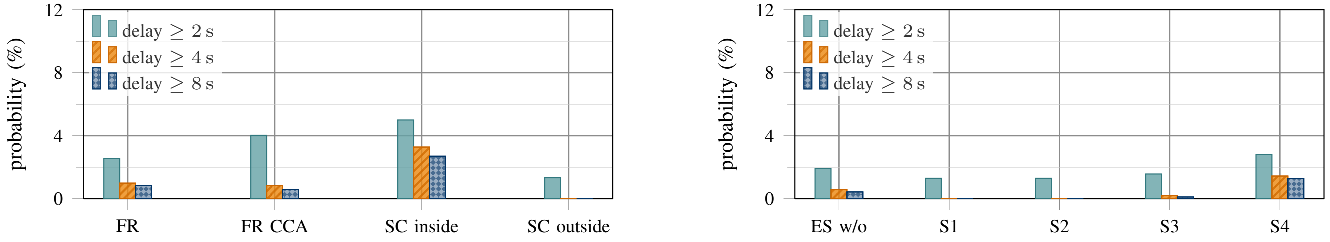
D. Spatial Mitigation Performance

The loss rate evaluations depicted in Fig. 10 show the benefits of the spatial mitigation technique. The S1 frequency assignment allows far located nodes to transmit inside the RA spectrum, while the half of nodes located closely are permitted to use interfered channels. This results in an absence of losses although the share ratio is increased to 50%. Scheme S3 also shows satisfying performance: slightly interfered nodes use sequences with relatively low share ratio, as depicted in Table II, which leads to a compensable amount of losses while increasing the share ratio to 71%. Loss rates increase heavily if the same sequences with relatively low share ratio are assigned to highly interfered nodes, depicted in scheme S4; thus, nodes located directly beneath the RA should be omitted from channels overlapping with B_S.

The mean delay depicted in Fig. 11 shows performance similar to the undistorted case for schemes S1 and S2. While usage of S3 increases the delay by only 8% if RA A1 is used, the mean delay is increased by 63% in aircraft equipped with RAs of type A2. However, the spatial mitigation technique shows better performance than unadapted hopping patterns, single channel systems and enhanced channel hopping without synchronization.

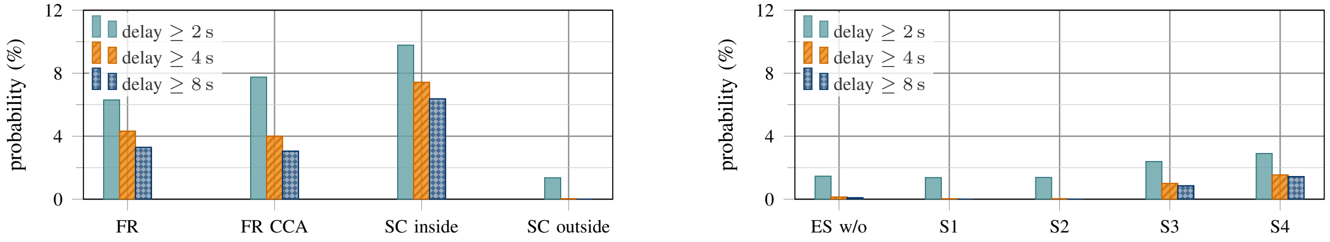
To sum up and compare all different techniques towards their applicability in WAIC systems, Fig. 12 depicts the delay probability. Three different delay boundaries are defined and the probability, that a packet experiences a higher delay than the boundary is shown. Without adapting to the interference environment, packets with high delays are more likely, e.g. packets with a delay higher than 2 s occur three times more likely if only one channel is used. The situation even impairs if interference of faster RAs is present; packets with a delay greater than 2 s are seven times more likely. In the presented scenario, usage of CCA mainly affects packet delays between 2 s and 4 s; e.g. as depicted in Fig. 12(a) the violation probability increases from 2.5% to 4%.

As depicted in Fig. 12(b) and Fig. 12(d), the presented mitigation techniques ease increasing delays. Spatial mitigation



(a) Interference impact of RA A1.

(b) Mitigation techniques with interference of RA A1.



(c) Interference impact of RA A2.

(d) Mitigation techniques with interference of RA A2.

Fig. 12. Probability that packet delays higher than specified boundary occur in WAIC system.

schemes S1 and S2 reassure delay probabilities similar to the undistorted case. Even schemes S3 and S4 perform significantly better than traditional channel usage and additionally increase the share ratio up to 75%.

E. Discussion

The suggested channel hopping mitigation technique increases reliable spectrum usage by 43% in aircraft equipped with slower RAs if additional effort is spent to synchronize the WAIC system with the RA signal. Exploiting the spatially bounded impact is in general more robust, reassures interference-free performance with increased spectrum usage of 50% and can be employed easily with ISA100.11a-compliant hardware. Thus, it is expected that hardware manufacturers adapt spatial interference mitigation principles for future WAIC-compatible hardware.

VII. CONCLUSIONS

The operation of WAIC for safety-related communication within the aircraft offers several benefits from weight and maintenance cost reduction to lower environmental impact and increased flexibility of aircraft equipping.

We showed that RAs in aircraft strongly impact TDMA- and channel-hopping-based WAIC systems operating in the 4200 MHz to 4400 MHz band. We presented detailed simulation results on the harmful interference impact, e.g. resulting in up to ten times higher transmission delays. While the spatial mitigation technique offers robust and solid mitigation, the time-frequency adaption requires more effort to be applied. Upon this knowledge, it can be concluded that interference of on-board RAs in WAIC-equipped aircraft is mitigated reliably.

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