Empowering Heterogeneous Communication Data Links in General Aviation through mmWave Signals

Citation
Wang, W., Talvitie, J., Adamova, E. J., Fath, T., Korenciak, L., Valkama, M., & Lohan, E. S. (2019). Empowering Heterogeneous Communication Data Links in General Aviation through mmWave Signals. *IEEE Wireless Communications*, *26*(6), 164-171. [8926332]. https://doi.org/10.1109/MWC.0001.1800593

Year
2019

Version
Peer reviewed version (post-print)

Link to publication
TUTCRIS Portal (http://www.tut.fi/tutcris)

Published in
IEEE Wireless Communications

DOI
10.1109/MWC.0001.1800593

Empowering heterogeneous communication data links in General Aviation through mmWave signals

Wenbo Wang*, Jukka Talvitie*, Eva Jošth Adamová†, Thilo Fath‡, Luboš Korenčiak†, Mikko Valkama*, and Elena Simona Lohan*,
*Tampere University, Finland, †Honeywell, Czech Republic, ‡Airbus, Germany

***Abstract*—We study data transfer links that would enable development of low-cost technologies for increasing safety of general aviation (GA). The solution proposed here is to supplement the existing cmWave solutions with mmWave cellular signals in order to better handle interferences and to reach lower outage probabilities and higher throughputs. Moreover, cellular solutions have the advantage of re-using existing or planned infrastructure, and thus they are expected to require minor additional investments. Our paper aims both at shedding some light on the terminology in GA field and at proposing future viable data-link solutions in GA. We also survey the existing solutions, challenges, and opportunities related to the wireless communication links in GA, and we present several case studies related to the achievable outage probabilities and throughputs under rural and urban scenarios of low-altitude GA vehicles. We conclude that supplementing the existing cmWave wireless links with mmWave wireless connections is a workable solution for affordable communication links for low-altitude GA aircraft.**

I. INTRODUCTION AND MOTIVATION

Currently most of the aircraft operations belong to the *manned aviation* (MA) that refers to operations by aircraft that are piloted by a human on board. At the same time, as the number of operational unmanned aerial vehicles (UAVs) is growing fast, more and more *unmanned aviation* (UA) operations are expected in the future.

The *general aviation* (GA) is defined by International Civil Aviation Organization (ICAO) as all civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire. However, this definition is rather broad and it does not classify comprehensively the GA operation class from a research point of view. An essential characteristic of GA which is not reflected in the ICAO definition is that GA is commonly understood as a subclass of the MA class. One important contribution of this paper is to clarify the GA notion in a more detailed manner, as shown in Fig. 1, where categorization of separate aviation classes is visually illustrated.

Nowadays, MA has one of the lowest probability of accidents out of all the means of transport. This was achieved by various systems, technologies, and procedures. In particular, the communication, navigation, and surveillance (CNS) technologies installed on board of aircraft play crucial role to lower the probability of accidents. However, there are still many aircraft that use for example just one piece of communication equipment: the radio (wireless) link for voice communication with air traffic control. Almost all of these aircraft with limited equipment operate under the general aviation category and fly typically only in low altitudes (below 3000 m). GA incorporates also business aviation and it is known that the business jets are among the best equipped aircraft currently flying. Thus, we would like to clarify that for the rest of this paper we use the term *low-altitude GA* (laGA) referring only to a part of GA operations at low altitude and uncontrolled airspace (i.e., explicitly excluding business aviation).

The reason for limited equipment onboard of laGA aircraft is that they are usually used for non-commercial activities (e.g., recreational or philanthropist purposes, research on wild life and climate changes, etc.) and the CNS technologies used for other aviation classes are simply too expensive to be used for these purposes. The UAVs represent another category of aircraft with highly varying level of CNS equipment. Even a small UAV with weight of 2 kg can kill a human when it falls on his/her head or it can seriously damage or even destroy a propeller or a turbofan engine. The rapidly rising number of UAVs, and hence also the risk of potential collisions with other aircraft sharing the same airspace, is a challenge for all of the MA, but mostly for laGA aircraft since they will share the low-altitude airspace with UAVs.

Thus, it is very important to develop affordable CNS technologies for laGA, keeping in mind that many novel solutions that are relevant for laGA, they may become also relevant for UAVs, which in the future will share the same airspace with laGA. These technologies will require a data transfer infrastructure to exchange the information with ground (e.g., traffic management) and with other aircraft that will operate in low altitudes. Such technologies also need to be affordable and quickly deployed. Using the existing and developing cellular infrastructure also for data-link needs of laGA has a large potential to meet all the above requirements.

The use of cellular infrastructure for air traffic at low altitudes has various challenges, e.g., how to decrease the miscommunication errors [1] or how to decrease the outage probabilities. The outages here refer to the situations when the received signal-to-interference-plus-noise ratio (SINR) is below a certain threshold, and thus it is not sufficient to establish and maintain a reliable wireless data link. In addition, both intentional and unintentional wireless interferences are increasing with an increased air traffic, and thus supplementary solutions to the existing ones need to be found. For all of the above reasons, it is highly beneficial to know or to approximate *the path loss* that refers to the deterministic decrease in the signal power due to the wireless propagation over a certain

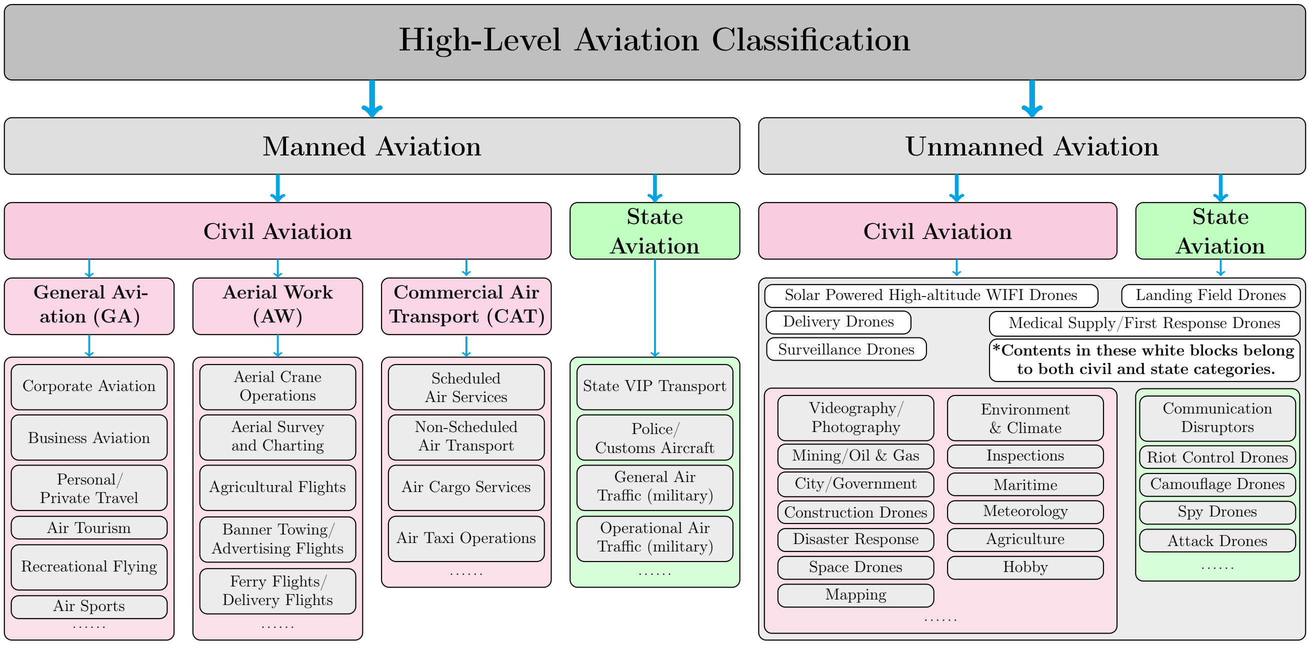

Fig. 1: The main aviation classes.

distance.

The aim of this paper is to promote research in cellular wireless technologies to support low-cost wireless data transfer for aviation purposes, especially for unequipped laGA aircraft and for UAVs sharing the same airspace with laGA aircraft. This will ensure safer future operations, as well as better airspace access for laGA.

We illustrate in a concise manner the existing solutions, the current open challenges, and the opportunities for future laGA data link solutions. We postulate that using the mmWave frequency bands (i.e., data links at carrier frequencies above 30 GHz, that are also to be used for the upcoming 5G cellular communications) can offer viable and robust supplementary solutions to the existing ones, despite their increased path losses. The adoption of mmWave solutions is motivated by the facts that there is currently very low amount of interference in mmWave bands, that beamforming with large or massive multi-antenna processing can boost the wireless channel capacity, and that lower outage probabilities are possible with astute mmWave processing, which would increase the connectivity availability and thus would increase the aircraft safety. More about the mmWave benefits and challenges is discussed in Section IV. In this paper we analyse two concrete case-studies for low-altitude aerial vehicles, namely urban macrocell and rural macrocell cases, and we present the outage probabilities under certain receiver sensitivity requirements, as well as the achievable throughputs (measured in megabits per second or Mbps).

Related Work: Some major trends in wireless communications nowadays, which are likely to affect also the laGA domain in the future, are towards automation, remote controlling, cloud-based processing, and software-defined networking. The communications in the aviation domain, and in particular in laGA domain, make no exception from these trends, but their developments move at a much slower pace than the developments in the terrestrial wireless architectures. This slower-paced development is most likely due to the fact that there are more stringent safety and reliability targets involved. Other emerging trends in aviation, not addressed here, are the Aeronautical Ad-Hoc Networks (AANET) [2], aiming at improved and more reliable communications both between aerial vehicles and between an aerial vehicle and the ground networks, such as cellular (e.g., 5G [3]) and Internet of Things (IoT) networks. The need for enhanced surveillance, communication, and flight management capabilities in MA has been recently emphasized in [4].

As shown in Fig. 1, according to the usage, the aviation domain is typically categorized into manned and unmanned aviation. Each category (i.e., MA and UA) can be further divided into civil aviation and state aviation. While GA aircraft and UAVs fall in different categories as illustrated in Fig. 1 (MA versus UA), they often share the same airspace. Thus, wireless communication solutions for GA are also relevant for UAVs. The GA category is a sub-category of manned civil aviation and laGA is sub-category of GA. The laGA aircraft include utility aircraft (e.g., Cessna 172), sailplanes, aerobatic aeroplanes, research helicopters, etc.

II. KEY EXISTING TECHNOLOGIES, CHALLENGES, AND OPPORTUNITIES FOR THE DATA LINKS IN LAGA

In this section, we provide a short description of few MA data-transfer technologies that are or might be relevant to the laGA aircraft in the future. The first two technologies listed here are the only ones currently in use for laGA aircraft:

- The *VHF Data (or Digital) Link mode 2 (VDLm2)* is the main version of VHF Data Link and it is currently the primary mode used in the wireless communications links for MA. The VDLm2 uses a differential 8-PSK

modulation and transmits at carrier frequency of around 136 MHz with signal bandwidths of 25 kHz. Typical throughputs in VDLm2 are around 31.5 kbps at physical layer.
- Another data-link solution in MA is the *High Frequency Data Link (HFDL)*, reaching low throughputs of up to 1.8 kbps.

VDLm2 and HFDL are air-to-ground (A/G) technologies. In addition, few more expensive solutions, based on satellite communications such as Inmarsat and Iridium, exist and they are mostly used by high-cost GA aircraft. We would like to emphasize the fact that currently, Inmarsat and Iridium technologies and the other experimental solutions described below are not used for laGA, but they are listed here for the sake of completeness and as the focus is on technologies that might be relevant also to laGA in the future:

- *Inmarsat* is both a wireless communication solution and a company focusing on satellite-based communications; their broadband connectivity solutions rely on air-to-satellite (A/S) wireless transmissions, mostly in L-band (i.e., 1–2 GHz). In downlink high throughputs of 50 Mbps are achievable via Inmarsat Global Xpress solutions.
- *Iridium*, like Inmarsat, is another solution, named after a company offering broadband connectivity to passengers of business GA aircraft and commercial airlines, based on satellite communications technologies in L bands. Iridium has its own constellation of 66 operational units. Achievable throughputs are lower than with Inmarsat, and in downlink they can go up to 1.5 Mbps in Iridium NEXT.

Additional solutions discussed in the next bullet points are either in experimental phase or in research phase.

- *European Aviation Network (EAN)* is an experimental communication data link for aviation, built by Inmarsat and Deutsche Telekom and scheduled to become fully operational in 2019. EAN integrates satellites and A/G connectivity networks, using cellular Long Term Evolution (LTE) ground base stations, operating also in L and S cmWave frequency bands. The applicability of EAN solution in laGA is still questionable, as the current EAN business model is focused mainly on the high-altitude commercial aircraft for on-board passenger entertaining broadband services.
- *L-band Digital Aeronautical Communications System* (L-DACS) is another experimental communication data link A/G solution under standardization since Dec 2016. It is based on orthogonal frequency division multiplexing (OFDM) and sharing many concepts with the 4G/LTE cellular communications. L-DACS currently uses L band (cmWave), which interferes with Distance Measuring Equipment (DME) systems used for localizing the aircraft with respect to a benchmark station. Achievable throughputs in L-DACS are up to 1.3 Mbps.
- *Broadband Aeronautical Multi-Carrier system (B-AMC)* is one L-DACS variant. B-AMC currently supports A/G mode, but extensions to A/A mode are currently under investigation. Achievable throughputs in B-AMC are around 300 kbps.
- *Aeronautical Mobile Airport Communication System (AeroMacs)* has also been proposed by Eurocontrol and Federal Aviation Administration (FAA) as a solution to modernize the aircraft communication links. It is based on the commercial 4G WiMAX specifications and it is meant for operation in C-bands, at around 5 GHz, for short-range high data-rate communications, with throughputs up to 10 Mbps.

As seen so far, most of the existing wireless solutions for communication data links use sub-GHz and GHz cmWave signals below 7 GHz and are typically affected by unintentional interference from other aviation signals or ground communication networks (e.g., LTE, FM broadcasting, etc.) In addition, the current spectrum below 7 GHz is very congested not only with other CNS signals used in aviation, but also with signal used in non-aviation systems. Therefore, to increase the robustness, and to be able to offer broader frequency diversity, a complementary solutions should move to higher than 7 GHz frequencies, in particular towards mmWave spectrum, namely frequency bands above 30 GHz.

Supplementing currently existing solutions with mmWave-based solutions can bring several benefits, as described in Section IV.

Table I summarizes the existing data links in MA, by pointing out the current usage of frequency bands, and the challenges and opportunities brought by each of these frequency bands. As seen in Table I, there is a large number of various communication solutions currently available, spanning over multiple frequency bands, but even such a significant number seems not to be sufficient for the future dense and complex airspace [5]. This is because each of the current solutions has its limitations, as illustrated in the fourth column in Table I. As seen in the previous section, the sub-GHz and GHz microwave solutions (i.e., the so-called cmWave solutions) are currently mostly deployed in crowded frequency spectra, namely below 7 GHz, where they have to deal with various inter-system interferences.

We postulate that, in order to solve the current limitations, the future communications for laGA should rely on multi-link capabilities, mmWave communications with localized interferences to supplement the cmWave communications, and multi-aircraft collaborations. The advantages of the communications above 8.7 GHz are illustrated in the last column and last row of the Table I. The mmWave bands according to the definition accepted by the wireless communication community refers to frequencies above 30 GHz. As the bands above 8.7 GHz are currently used very little or unused, there is a low amount of inter-system interference in these bands. In addition, as the carrier frequency increases, the path losses are also higher, meaning that only the transmitters in a vicinity of a communication link would interfere with that communication link (i.e., we have a localized interference, where interference management becomes easier [3]). In addition, larger contiguous bandwidths are available at mmWave bands, e.g., even 100 MHz of contiguous bandwidths, enabling higher throughputs in communication and higher positioning accuracy in navigation applications.

Band	Frequency ranges	Example use in aviation	Challenges	Opportunities
HF	3–30 MHz	2850–22000 kHz: A/G communication (HF voice and data) 3023&5680 kHz: Search and Rescue	Possible interferences from FM broadcasting; Many sub-bands here reserved for military aviation applications	Low path losses; Large coverage areas; Well-established/traditional aviation solutions
VHF	30–300 MHz	117.975–137 MHz: A/G (voice and data) and A/A communication (voice) 129.15–136.9 MHz: VDLm2, ACARS/HFDL	Crowded frequency bands and interferences from other systems; Low throughputs	Path losses slightly larger than in HF band; Coverage areas still high; Well-established/traditional aviation solutions
UHF or L	0.3–3 GHz	960–1164 MHz: C2 terrestrial link 1.61–1.62 GHz: Iridium 1–4 GHz: Inmarsat	Most crowded frequency bands for aviation are between 1 and 4 GHz; High interferences up to 4 GHz; Current use in GA limited to business jets	Enhanced capacity compared to sub GHz bands; Potential to use existing cellular and IoT infrastructure
SHF or C	3–7 GHz	5.03–5.09 GHz: C2 satellite link AeroMACS	Interferences from other systems, as C band is also used for satellite communications and some synthetic aperture radars (SARs)	High capacity/high throughputs achievable; C band suffers of lower interferences than HF and L bands
SHF (X, Ku, K, Ka bands), V and W	7–110 GHz	Used very little in wireless links for aviation systems (e.g., JetWave)	Very high path losses; Short range; Gaseous absorption above 60 GHz	Very high throughputs achievable; Low and localized interferences; Miniaturized antenna arrays; Efficient beamforming solutions possible

TABLE I: Existing and potential communication data-link technologies in manned aviation.

III. MODELLING THE LOW-ALTITUDE GENERAL AVIATION CHANNELS

A path-loss model of a wireless data link (i.e., A/A, A/G, or A/S) has typically three components: i) a deterministic path-loss component that is distance and frequency dependent; ii) a random shadowing component, modelling the large-scale fluctuations in the path losses, and iii) a random fading component, modelling the small-scale (rapid) fluctuations in the received signal strength. In addition, most of these models are split into a line of sight (LOS) part and a non line of sight (NLOS) part, with an associated LOS probability to define the transition between the two parts. Channel models in aviation were studied for example in [6]–[13], and a summary of the most encountered models for laGA links is shown in Table II.

a) Path losses in A/G channels: The A/G channels (sometimes referred to as A2G or G2A to also illustrate uplink/downlink connectivity) differ from the ground propagation channels in typically higher elevation angles, higher LOS probability and less multipath to deal with [14]. One of the most encompassing A/G channels in the current literature are the recent 3GPP channels [6] covering carrier frequencies up to 100 GHz and aircraft altitudes up to 300 m. The 3GPP aerial channel models [6] expand the urban macrocell (UMa), rural macrocell (RMa) and urban microcell (UMi) terrestrial channel models to aerial operations. The most relevant 3GPP channel models, in the context of laGA, are UMa and RMa, as the base station antenna in UMi is below the roof-top level, and thus unable to serve with adequate quality in-flight aerial vehicles. Aerial channel models could be considered in two parts, namely below 300 m part and above 300 m part. The one above 300 m altitude typically is Free Space Loss (FSL) [9], possibly with some correction parameters, such as those used in the IF-77 FAA channel model, recently re-published by ITU under the name of ITU-R P.2345-0 channel model [7].

b) Path losses in A/A channels: The A/A models assume a base station installed in the moving aircraft and a receiver also installed in another moving aircraft. The A/A models existing in the literature assume 100% LOS and they rely either on a modified FSL model (e.g., by changing slightly the path loss coefficient) or on a simplified path-loss model which is frequency independent (it depends only on the distance between the aircraft). A/A path loss modelling is quite limited in the existing literature.

c) Path losses in A/S channels: A/S channel models are even scarcer in the current literature than A/A models and they typically assume FSL and LOS scenarios.

d) Shadowing and fading: The path-loss models described so far depend on the link type, e.g., A/G, A/A, or A/S. The shadowing and fading models are typically modelled by similar distributions, independently of the link type (i.e., the same statistical distributions with different parameters). The vast majority of papers reporting measurement-based shadowing and fading distributions for aerial vehicles specify a Gaussian distribution in logarithmic scale (i.e., log-normal distribution) for the shadowing effects (i.e., the received signal strength large-scale fluctuations in dB scale obey a Gaussian zero-mean distribution) and a Rician distribution (typically with a strong Rician factor) for the fading effects.

The 3GPP UMa and RMa models [6] are frequently regarded as the benchmark in various literature studies. The Huawei UMa and RMa models [11] are derived from 3GPP models with additional measurements fitting at cmWave bands. The measurements-based fitting is treated as a correction figure to be added to the 3GPP models.

IV. BENEFITS OF MMWAVE BANDS AND CASE STUDIES IN RURAL AND URBAN AREAS

We start first by describing the potential benefits of using mmWave bands for laGA wireless communications.

1. **Better interference rejection capability**: If the interference affects only some of the available frequency

Model	Main parameters	Component	Link type	Observations	Reference
Free Space Loss (FSL)	3D distance, carrier frequency	Path loss	A/G A/A, A/S	Aircraft heights above 300 m	[9], [13]
3GPP	Horizontal distance, carrier frequency, aircraft altitude	Path loss, shadowing, fading	A/G	Aircraft heights up to 300 m; Carrier frequencies below 100 GHz	[6]
FAA IF-77/ ITU-R P.2345-0	3D distance, carrier frequency, mean surface refractivity, antenna heights, elevation angle, surface conductivity, etc.	Combined path loss, shadowing, fading, atmospheric effects	A/G, A/A, A/S	Carrier frequencies below 20 GHz; Based on FSL path loss; Many empirical parameters needed as inputs	[7]
Huawei A/G	Horizontal distance, carrier frequency, aircraft altitude	Path Loss	A/G	These are 3GPP UMa and RMa models with a correction factor	[11]
Gaussian in log scale	-	Shadowing	A/G, A/A, A/S	Shadowing variance varies according to LOS/NLOS profile	[8], [10]
Rician	-	Fading	A/G, A/A, A/S	Rician factor varies according to the link type	[8], [12], [13]

TABLE II: Summary of main channel models suitable for laGA.

bands, an optimally combined solution can choose to operate in the frequency band with the higher SINR. As mmWave signals have higher path losses (as the path losses are inversely proportional with the square of the carrier frequencies), long-distance interferer has lower effects in the mmWave than in the cmWave bands.

2. **Coherent combining gain**, namely a system operating on N frequency bands and combining the N signals in a coherent manner has a theoretical $10\log_{10}(N)$ gain in the signal-to-noise ratio compared to the single-frequency system. Thus combining the existing cmWave solutions with mmWave solutions would enhance the operational SINR.
3. **Higher throughput is theoretically achievable**, due to the higher available contiguous bandwidths as we move at higher frequencies, above 30 GHz.
4. **Lower outage probabilities** are a result of better operational SINR. Indeed, a better operational SINR is achievable due to a lower interference in mmWave than in cmWave at the moment, due to the possibility of using beamforming and massive multiple-input multiple-output (MIMO) to enhance the SINR, as well as due to the diversity gains achievable by combining several carrier frequencies, as mentioned above.

Secondly, we would also like to point out that the use of mmWave bands raises the following challenges which need to be addressed:

1. **Limited ranges**: the higher the carrier frequency, the weaker the received signal power is, and the distance-based losses (called path losses) are major factors limiting the achievable communication ranges and the coverage areas of the ground base station. A high density ground infrastructure can increase the range, but this would also increase the infrastructure deployment costs for mmWave-band transmission.
2. **Need for antenna up-tilting**: in order to communicate with the flying aircraft, the future cellular networks, such as 5G, must support also up-tilted antennas with associated additional components.
3. **Mobility**: to compensate the path losses in mmWave bands and to mitigate the interference in wireless links, the MIMO techniques are applied. The beam alignment for the high mobility user is challenging.

Thirdly, we present two case studies in rural and urban areas, by focusing on outage probabilities and throughputs as performance metrics, respectively. Outage probabilities are generally important metrics in studying the performance of wireless channels [15] and they are particularly relevant in aviation since the reliability of a communication link is directly related to the safety of people on-board of aircraft. We define the outage probability as the probability that the instantaneous SINR drops below a target SINR. The target SINR is related to the receiver sensitivity needed for the receiver to operate correctly, according to target metrics (e.g., bit error rates, symbol error rates, coverage area, etc.). For example, current LTE specifications specify a target minimum SINR $= -5$ dB. Future 5G receivers are likely to go down to operational SINR ≤ -30 dB [3], by taking advantage of beamforming and MIMO gains. Throughputs are obvious performance metrics when the target is to have some broadband services, such as on-board passenger entertainment. The second case study focuses on achievable throughputs under a more futuristic hypothesis, when broadband connectivity will also be available on laGA aircraft.

In the **first case study**, we compare cmWave performance with mmWave performance in terms of outage probabilities. We study the situation where the cmWave-based solutions are affected by interference (e.g., operational SINR $= -5$ dB), while the mmWave are in an interference-free case (e.g., operational SINR $= -30$ dB). The results are shown in Fig. 2. A receiver bandwidth of 5 MHz was considered for a fair comparison at all carrier frequencies. Five channel path models were selected among those in Table II, namely the FSL, UMa and RMa from 3GPP specifications [6], and UMa and RMa from Huawei model [11]. UMa cases correspond to urban scenarios, while RMa cases correspond to rural scenarios. The FAA model [8] was not included in our studies, as it depends on many unknown parameters, such as the geometry of the environment, the permittivity of the obstacles between the access nodes (or base stations) and aircraft, etc. The log-

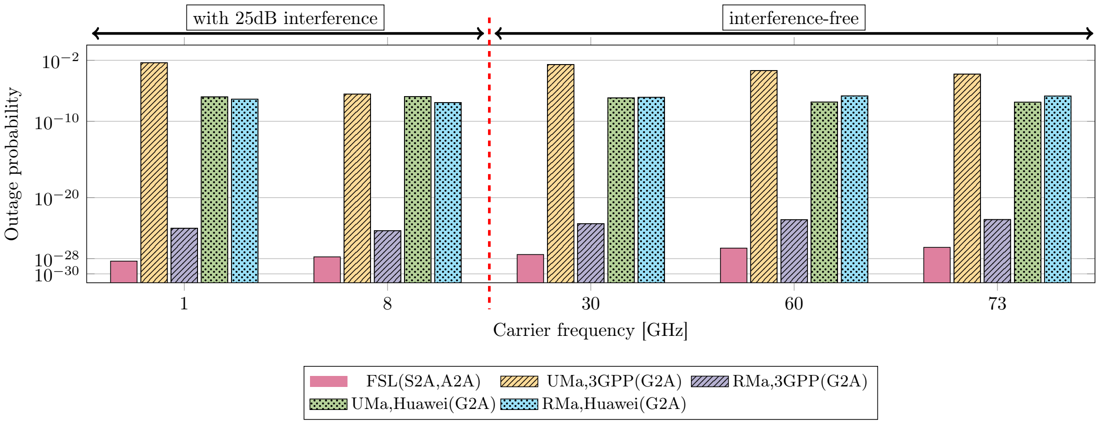

Fig. 2: Outage probabilities in interference-affected scenario in cmWave bands and interference-free scenario for mmWave frequency bands.

normal shadowing and Rician fading were also modelled for all these five channels. When the shadowing is specified in the model (i.e., the 3GPP models), the shadowing parameters from the models were used. In Huawei channel model, we used shadowing parameters from 3GPP for the Huawei UMa and RMa scenarios respectively. This means that in some cases the shadowing was stronger than in the others (e.g., RMa and UMa have slightly different shadowing parameters for both 3GPP and Huawei models). The fading was modelled similarly for all the five channels, according to a Rician distribution with Rician factor varying randomly between 7 and 9 dB. For FSL, a shadowing variance similar with 3GPP RMa LOS shadowing variance was used. In the simulations we used the quasi-LTE signal parameters for the parts including link budget calculations. We also assumed constant antenna gains. The full details on the technical parameters are available at [1] and are not included here due to lack of space. The outage probabilities shown in Fig. 2 range between 4.7×10^{-29} and 4.8×10^{-3} at cmWave bands (i.e., interference prone environment) and between 3.4×10^{-28} and 2.8×10^{-3} at mmWave bands (i.e., interference-free environment), according to the used channel model. FSL gives the lowest outage probabilities at each frequency bands, but they likely are quite unrealistic, as seen from the comparison with the other used channel models. If we compare the different channels considered in Fig. 2 we see that the 3GPP UMa model is the most pessimistic one. We can also see in Fig. 2 that the both Huawei channel models (RMa and UMa) give rather similar results in terms of outage probabilities. This probably happens because Huawei channel models were derived according to UAV-based measurement campaigns at two specific sites (classified as urban and rural), which might not have had sufficient feature to characterize comprehensively urban and rural areas. These results indicate that Huawei models seem to be less suitable than 3GPP models for a good analysis of path losses and outage probabilities for low-altitude GA aircraft.

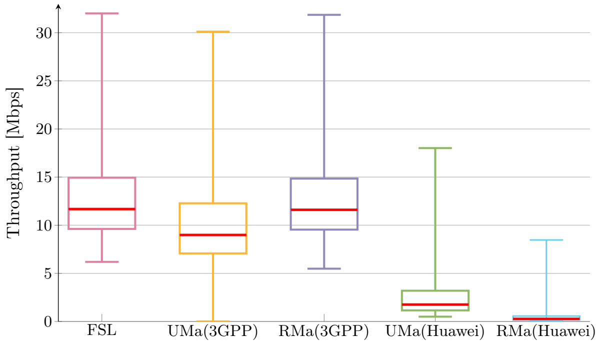

Fig. 3: Throughputs at 30 GHz frequency with 5 MHz bandwidth according to five channel models.

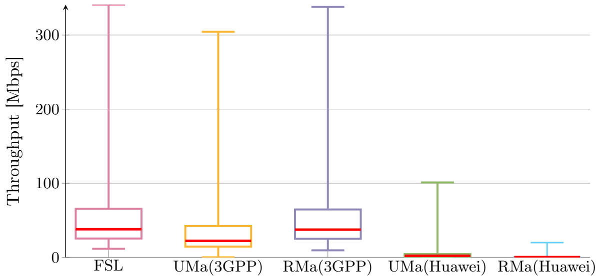

Fig. 4: Throughputs at 30 GHz frequency with 100 MHz bandwidth according to five channel models.

Our **second case study** focuses on mmWave only, assuming two different receiver bandwidths and taking throughput as the performance metrics. The throughput is a critical criterion in wireless communications, that indicates what kind of operations could be implemented in the channel. We simulated the throughput values based on the five above-mentioned channel models, at 30 GHz carrier frequency, corresponding to the lower bound of the mmWave bands. Both small and large bandwidths were considered (5 MHz in Fig. 3 and 100 MHz in Fig. 4) with a capacity efficiency factor of 0.7. The small-bandwidth case was selected for a fairer comparison to the cmWave bands and in order to provide the lower bounds on the achievable throughputs, while the large-bandwidth case reflects the future trends in wireless communications. The height of aircraft was uniformly varied from 50 m to 3 km, which corresponds to airspace G where most of the flying laGA

---

[1] https://bit.ly/2Qg3vC3

aircraft operate. We focus on the **downlink** transmission (i.e., ground-to-air mode), with a base-station transmit power of 43 dBm and a receiver noise figure of 8 dB, in accordance with current LTE specifications (the parameters for simulations of the second use case are available at [1]). The term downlink here is used according to the wireless communication terminology, meaning the link from the (ground) base station towards the aircraft, by distinction with the uplink transmissions, which are from the mobile or aircraft towards the base station.

In the box plots (i.e., Fig. 3 and Fig. 4), we assumed the upper whisker as the 99.7th percentile, the lower whisker as the 0.3th percentile, the upper quartile as the 75th percentile and the lower quartile as the 25th percentile. As expected, the throughput under FSL channel model gives the most promising results, its median is around 12 Mbps with 5 MHz bandwidth and around 38 Mbps with 100 MHz bandwidth. However, such a value is unlikely to be achieved in practice, as FSL is a rather idealistic channel model. Under the 3GPP channel models, with 5 MHz bandwidth, the median values of throughput are about 9 Mbps and 12 Mbps in UMa and RMa scenarios, respectively. Meanwhile, with 100 MHz bandwidth the median values are 22 Mbps and 37 Mbps in 3GPP UMa and RMa scenarios, respectively. 3GPP RMa scenario converges in fact to FSL scenario for altitudes above 300 m. According to the Huawei channel model, the median values of both UMa and RMa scenarios are below 3 Mbps with both 5 MHz and 100 MHz bandwidth, which shows that this model is the most pessimistic among the considered models and can be considered as a lower bound on the performance.

V. CONCLUSIONS

In this work, we have reviewed the major challenges and potential technology solutions in the communication data links used in laGA and we have pointed out low interference level, reasonable outage probability and high achievable throughputs of the use of future mmWave signals to supplement the existing cmWave aviation links. The discussion was focused mostly on the physical layer aspects of laGA, as this physical layer design is one of the most critical ones when designing new communication solutions. The advantages of a mmWave-based approach have been shown in terms of achievable outage probabilities and throughputs under five different channel models and for different available channel bandwidths. The predicted values highly depend on the underlying path-loss modelling, with FSL giving overly optimistic upper bounds and with Huawei channel models giving the lower bounds in throughput performance. We recommend the use of 3GPP channel models in the context of laGA data links, as they not only provide an average performance among various considered models, but they are also widely accepted by the research community. Despite the higher path losses at increased carrier frequency, it could be seen that the outage probability of mmWave signals was close to the one for cmWave signals. Therefore the usage of mmWave signals is a promising supplementary solution in addition to the existing ones. Open research directions are the impact of the antenna radiation patterns on the outages and throughputs, modelling more accurately the link budgets according to the upcoming 5G specifications, and investigation of navigation, tracking, and positioning capabilities of the wireless signals for laGA.

ACKNOWLEDGEMENT

This work was supported by SESAR Joint Undertaking (SJU) in project EMPHASIS (grant 783198). The opinions expressed herein reflect the authors' view only. Under no circumstances shall the SJU be responsible for any use that may be made of the information contained herein. This work has been also partially supported by the Academy of Finland (grant 313039).

REFERENCES

[1] B. Molesworth and D. Estival, "Miscommunication in general aviation: The influence of external factors on communication errors," *Safety Science*, vol. 73, pp. 73–79, March 2015.

[2] Q. Luo and J. Wang, "Multiple QoS parameters-based routing for civil aeronautical ad hoc networks," *IEEE Internet of Things Journal*, vol. 4, pp. 804–814, June 2017.

[3] A. Gupta and R. K. Jha, "A survey of 5G network: Architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, July 2015.

[4] Y. Lim, V. Bassien-Capsa, S. Ramasamy, J. Liu, and R. Sabatini, "Commercial airline single-pilot operations: System design and pathways to certification," *IEEE Aerospace and Electronic Systems Magazine*, vol. 32, pp. 4–21, July 2017.

[5] D. W. Matolak, "Hyper-spectral communications, networking ATM as foundation for safe and efficient future flight: Transcending aviation operational limitations with diverse and secure multi-band, multi-mode, and mmWave wireless links: Project overview, aviation communications and new signaling," in *2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC)*, pp. 1–7, September 2017.

[6] "3GPP - 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on enhanced LTE support for aerial vehicles (release 15)." 3GPP TR 36.777 V15.0.0, http://www.3gpp.org/DynaReport/36-series.htm, January 2017.

[7] "ITU - Report ITU-R P.2345-0 (08/2015), Defining propagation model for Recommendation ITU-R P.528-3." P Series, Radiowave propagation, August 2015.

[8] D. W. Matolak and R. Sun, "Air-ground channel characterization for unmanned aircraft systems; part i: Methods, measurements, and models for over-water settings," *IEEE Transactions on Vehicular Technology*, vol. 66, pp. 26–44, January 2017.

[9] J. Naganawa, J. Honda, T. Otsuyama, H. Tajima, and H. Miyazaki, "Evaluating path loss by extended squitter signals for aeronautical surveillance," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1353–1356, December 2017.

[10] R. Amorim, P. Mogensen, T. Sorensen, I. Z. Kovacs, and J. Wigard, "Pathloss measurements and modeling for UAVs connected to cellular networks," in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, pp. 1–6, June 2017.

[11] K. Wang, R. Zhang, L. Wu, Z. Zhong, L. He, J. Liu, and X. Pang, "Path loss measurement and modeling for low-altitude UAV access channels," in *2017 IEEE 86th Vehicular Technology Conference*, pp. 1–5, Sep 2017.

[12] E. Yanmaz, R. Kuschnig, and C. Bettstetter, "Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility," in *2013 IEEE 32nd Conference on Computer Communications (INFOCOM)*, pp. 120–124, April 2013.

[13] R. Sun and D. W. Matolak, "Air-ground channel characterization for unmanned aircraft systems; part ii: Hilly and mountainous settings," *IEEE Trans. on Veh. Technology*, vol. 66, pp. 1913–1925, Mar 2017.

[14] N. Ahmed, S. S. Kanhere, and S. Jha, "On the importance of link characterization for aerial wireless sensor networks," *IEEE Communications Magazine*, vol. 54, pp. 52–57, May 2016.

[15] T. D. Cola and M. Mongelli, "Adaptive time window linear regression for outage prediction in Q/V band satellite systems," *IEEE Wireless Communications Letters*, pp. 1–1, April 2018.