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Performance Study on Seamless DA2GC for Aircraft Passengers Toward 5G

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Abstract – Mobile users seek for ubiquitous broadband connectivity even during a flight above the clouds. As many passengers are expected to be connected to high-speed Internet, robust and high-capacity direct air-to-ground communication (DA2GC) to connect the aircraft with the ground cellular network is particularly attractive. In this paper, we assess the capacity limitations of DA2GC link provided to an aircraft by employing currently available 4G radio technologies. Further, we study different capacity enhancement techniques toward 5G such as an implementation of Multi-User Multiple Input Multiple Output (MU-MIMO) or coordinated beamsteering to improve DA2GC capacity. We also compare DA2GC performance with connectivity offered by satellites. According to our results, DA2GC network extended for techniques toward 5G can improve capacity available per aircraft nearly by 100 Mb/s in comparison with the 4G DA2GC network, assuming 20 MHz bandwidth is exploited. Although the maximal capacity provided by the 5G DA2GC network and satellite communication is the same, satellite communication exhibits only 40 Mb/s for 10 000 deployed satellites in average. To incite future investigation in this field, this paper also outlines open challenges and research directions toward more efficient DA2GC.

Index Terms — DA2GC, 4G networks, 5G networks, satellite communication, network throughput, capacity;

I. INTRODUCTION

In the recent decade, the worldwide volume of flight traffic and number of transported passengers have risen significantly every year. With rising demands of mobile users on the capacity of wireless networks, a missing connection on board aircraft starts serious dissatisfaction of passengers [1]. Therefore, airline companies have started providing Internet access to passengers. Several initiatives and project consortiums dealing with air-to-ground (A2G) communication were established in recent years (e.g. [2]). Such projects mainly focused on two connectivity solutions regarding how to deliver Internet connection to users and aircraft's systems represented by a machine type communication (MTC) on board: direct air-to-ground communication (DA2GC) and satellite communication (SC). The main objective of this paper is an assessment and comparison of different technologies used for A2G communication.

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Fig. 1. Structure of A2G communication including DA2GC and SC with services available for onboard passengers, crew and MTC.

In the case of DA2GC, Internet connection is supplied in the same way as a connection for regular terrestrial mobile users. It means aircraft are connected via a direct link to direct air-to-ground eNodeBs (DA2G-eNBs), as shown in Fig. 1. The main advantage of the DA2GC solution is relatively easy and cheap deployment of DA2G-eNBs. DA2GC can be quickly introduced for airspace above the ground but cannot be easily provided above the sea to achieve worldwide service. In the case of SC, the communication between a ground station and an aircraft is relayed by satellites (see Fig.1). This approach provides global coverage. However, the main constraints of SC compared with DA2GC consist in higher communication delay and limited achievable data rate for the overall system. According to [3], currently, only 36% of all aircraft are equipped with onboard Internet connection provided mostly via satellites. Available satellite A2G solutions exploit mostly S (2 – 4 GHz), Ku (12 – 18 GHz) and Ka (26.5–40 GHz) bands and offer maximally tens of Mb/s/aircraft. Since throughput available via satellite is insufficient, only 6% of aircraft are able to deliver high-speed connectivity enabling video streaming and other highly demanded services [3]. The possible way of overcoming this capacity limitation issue is exploitation of DA2GC.

One of the existing DA2GC solutions is the GoGo network. This network offers DA2GC in U.S. and Canada through more than 225 base stations [4]. GoGo network operates at 850 MHz with 2 MHz bandwidth (BW) for uplink and 2 MHz

BW for downlink by using 3G Code Division Multiple Access Evolution-Data Optimized (CDMA EvDO) standard. The network provides DA2GC capacities up to 10 Mb/s [4]. One of the first research papers dealing with DA2GC [5] focuses on propagation aspects of air-to-ground communication including antenna design. However, only a signal level is evaluated without assessment of signal quality or capacity. Moreover, the analysis covers only relatively low frequencies of up to 1 GHz, which is not considered in our paper. Current research dealing with DA2GC focuses mainly on performance analysis of different technologies. In [6], the authors prove the feasibility of Multiple Input Multiple Output (MIMO) in A2G communication. The authors present field measurements of low-altitude A2G MIMO channels. The propagation characteristics indicate that the spatial properties of the A2G channel will support MIMO communication. DA2GC can be exploited also by unmanned aerial vehicles, as introduced in [7]. The concept of low-cost microsatellites is introduced in [8]. Although the proposal is not primarily aimed at A2G communication, aircraft can also exploit available capacity through micro-satellites. The advantage of small low earth orbit (LEO) satellites is the low delay compared with geostationary earth orbit (GEO) satellite services mostly used by aircraft today. While some LEO constellations already exist, several new initiatives aim to build high-throughput LEO satellite networks. Particularly interesting are the concepts of OneWeb, SpaceX and LeoSat planning to deploy between 100 (LeoSat) and over 4000 (SpaceX) LEO satellites in the next few years [9]. DA2GC can be the primary system used for communication with aircraft over mainland due to its relatively low-cost, simple, and quick installation advantages [10]. However, to provide a complete solution, the future evolution of Internet connectivity for aircraft requires hybrid solutions where cooperation of satellites together with the DA2GC system is present. Therefore, this paper aims at assessment and comparison of two types of DA2GC networks and connectivity provided via satellites.

The main contribution of this paper can be listed as:

- Performance assessment of DA2GC based on current 4G LTE standards and on envisaged 5G mobile networks that utilize LTE together with advanced radio techniques such as antenna arrays enabling coordinated beamsteering, multi-user MIMO (MU-MIMO) and higher order modulations.
- Performance analysis of SC based on LTE standard with advanced techniques toward 5G.
- Comparison of different radio technologies in terms of signal quality and capacity available per aircraft under static and dynamic scenario.
- Proposition of a new mobility model based on real traffic behavior of aircraft.
- Outline of new challenges toward future DA2GC networks.

The rest of this paper is structured as follows. Section II gives an overview of challenges toward future DA2GC systems. In Section III, our aircraft mobility model exploited for dynamic analysis is introduced. Section IV describes radio access technologies and simulation settings. In Section V, results of performance comparisons are presented and discussed. The last section summarizes major conclusions and outlines future work.

II. CHALLENGES TOWARD FUTURE DA2GC

In this section, challenges toward future DA2GC are introduced and discussed. Firstly, we describe challenges related to spectrum and regulations. The second subsection defines challenges associated with advanced technologies and techniques of next generation wireless network. In the last subsection, business challenges, such as business models and new business opportunities, are outlined.

A) Spectrum and regulations

Dedicated spectrum bands for exclusive DA2GC use are only available in some regions of the world, such as North America where 4 MHz BW is exploited by GoGo. However, the peak capacity of the GoGo system is of 10 Mb/s [4] even if a single aircraft is connected. To provide sufficient quality of service, more spectrum is needed.

For efficient DA2GC, a strong need for spectrum harmonization among many countries is required. However, spectrum utilization in DA2GC may be perceived low if compared with terrestrial networks. Another challenge is the authorization of dedicated spectrum, which requires coordinated processes involving all participating countries. Sharing spectrum with other radio systems such as satellite or terrestrial systems can be a feasible option. The deployment geometry and airspace coverage requirements lead to difficult interference problems, which, however, can be mitigated or solved with system coordination techniques.

As part of its ongoing work on spectrum harmonization for DA2GC, the European Commission mandates for two of the unpaired 2 GHz bands only to allocate one of the bands in TDD mode, which leads to an own recommendation at The European Conference of Postal and Telecommunications Administrations (CEPT) Electronic Communications Committee (ECC) level [11].

The Mobile Satellite System (MSS) spectrum at 2 GHz in Europe, which was awarded in 2008 and which was supposed to have satellite deployment in 2011, permits a called Complementary Ground Component (CGC). Recently one of the rights holders, Inmarsat, has teamed up with Deutsche Telekom under the name European Aviation Network (EAN) to deploy an air-to-ground system [2].

In the U.S., several industry stakeholders have been putting forth arguments to the FCC to make available 500 MHz of spectrum for DA2GC in the 14 GHz range. Moreover, current research trends focus on even higher frequencies such as millimeter waves where even wider spectrum bands can be used for DA2GC.

There are many open issues with respect to spectrum bands that will be available for DA2GC communications and their harmonization. Since spectrum will be always a scarce resource, dynamic spectrum management techniques need to be developed as the aircraft moves between countries for interference cancellation and re-use.

B) Advanced communication technologies and techniques toward 5G

5G is currently being developed by the 3GPP mobile community to provide a leap in mobile systems capabilities. It is expected that early trial systems could be in operation as early as 2018 with large-scale deployments starting around 2020. One part of 5G is the continued evolution of LTE, and with several aggregated carriers and new multi-antenna functionalities, the LTE radio access is a clear candidate for future DA2GC systems.

Another part of 5G is the New Radio (NR) for which 3GPP standardization started in March 2016. It is a new radio access built around some key technology features that are particularly interesting for DA2GC:

- Large bandwidths, 100 MHz and more
- Very large antenna arrays
- Beamforming/beamsteering

The impact of large bandwidths is immediate on capacity while very large antenna arrays (thousands of antenna elements) allow improving antenna gain. Beamforming/beamsteering avoids interference caused by other DA2G-eNBs and is even able to accomplish multi-user spectrum reuse from within the same DA2G-eNBs. While not ready yet, the 5G NR should be viewed as a strong candidate for future DA2GC systems.

Besides NR, new techniques such as coordinated multipoint (CoMP) with coordinated scheduling/beamforming or joint transmission are investigated as open research issues in this field. One of the main challenges of CoMP employed in DA2GC is relatively high delay caused by sparse deployment of DA2G-eNBs. Moreover, DA2GC opens a field to exploit advanced communication techniques such as Non-orthogonal multiple access (NOMA), which can maximally exploit specific DA2GC environment with dominated Line of Sight (LOS) component.

C) Business challenges

To ensure the provision of Internet connection to passengers on board, emerging DA2GC business environment requires the creation of new business models with new roles for current players and the introduction of completely new entities participated on DA2GC. New roles should be adapted by current players such as airlines or terrestrial operators to accept new business opportunities. Besides these, new entities such as cabin system operators or A2G network operators could emerge.

The A2G network operator is a consortium of all involved terrestrial and satellite operators, which provides the connection for cabin system operators. A2G operator acts like a virtual operator, who buys network capacity from terrestrial and satellite operators and sell it to cabin operators who are responsible for the provision of network services for passengers on board [11].

Besides the regulatory environment, the value chain and business ecosystem for DA2GC are quite complex. There are many players involved to provide this technology to the end user. Business models need to be studied that clearly define roles of partners and leave room for different players to stimulate the market (such as Europe), differing from monopolistic solutions. A novel research directions are viable business models for all players participating in DA2GC. Besides this, modeling the costs of connections should be formulated differently including CAPEX and OPEX, presenting another open research direction.

III. AIRCRAFT MOBILITY MODEL

In order to model the movement of aircraft in our analysis, we have developed an aircraft mobility model in MATLAB. The developed model simulates the movement of aircraft in the European airspace. Each aircraft has its origin and destination point and a predefined path between two points. The set of origin and destination for aircraft consists in real positions of 40 major airports in Europe and 5 entry/exit

points to/from Europe. An origin and destination airport is selected for each aircraft based on real traffic density in each airport with uniform distribution.

All flights have a climb phase, a cruise phase and a descent phase with predefined characteristics different for each flight. Characteristics of each flight, particularly maximum speed, maximum altitude, climb and descent times, are derived based on observation of real aircraft [13]. In particular, each flight has a target altitude and a maximum flight speed used through its whole cruise phase. During climb and descent phases, the speed and altitude increase and decrease linearly, respectively. The average climb time is 25 minutes and average descent time is 30 minutes randomized with the normal distribution (see Table I).

In the simulation, 20 new taking-off aircraft are considered on average per minute. An aircraft starts at a randomly selected time and flies directly to the predefined destination. Although aircraft are usually forced into corridors during the cruise flight, direct paths between two airports are taken on short-haul flights [13]. Besides these aircraft with predefined paths, also 10 randomly flying aircraft are always present in the simulation as background aircraft that require connection. We assume that exact positions of aircraft, the serving DA2G-eNBs, and the serving satellites are known. It enables coordination between DA2G-eNBs and elimination of Doppler shift by opposite shifting of transmitting/receiving frequency.

IV. SYSTEM PARAMETERS

This section provides a description of the comparative analysis of A2G communication systems. In two subsections, the radio access technologies and the simulation settings are introduced.

The performance is evaluated in terms of signal quality and communication capacity available for one aircraft. Since the most of the communication traffic onboard passengers is downloading, the analysis is made for forward link (from DA2G-eNBs to aircraft). The full buffer data traffic model is employed in the simulation.

Regarding signal propagation, the forward link is dominated by the LOS component during all flight phases. Due to this, the classical free-space path loss model (1) affected only by distance d and frequency f is used for modeling path loss (PL). This model is used in both cases, between DA2G-eNBs and aircraft as well as between satellites and aircraft:

$$PL = \left(\frac{4\pi df}{c} \right)^2. \quad (1)$$

A) Radio access technologies

To provide a fair comparison of different types of A2G communications, we exploit LTE technology with the same BW equal to 20 MHz for both 4G and 5G DA2GC as well as for SC. If wider BW is employed, total capacity can be proportionally increased in all networks. In the case of the DA2GC forward link, wider BW can be obtained, for example, by reusing frequencies exploited for terrestrial networks. A wide unused BW is available in higher frequency bands where hundreds of MHz can be exploited especially by SC. However, in the case of SC, such large amount of deployed satellites cannot be used only for one purpose, such as provisioning only A2G communication. The connectivity should be offered also for other terrestrial applications. Therefore, BW dedicated for A2G communication would be only part of total BW available from SC.

i) 4G DA2GC network

The 4G DA2GC network is based on 3GPP LTE standard currently widely implemented in terrestrial networks. The selected frequency band for the 4G DA2GC network is 3.4 GHz [11]. To suppress interferences between two neighboring DA2G-eNBs, beamforming is exploited in the three horizontal 120-degree sectors of each DA2G-eNB. Within each sector, the available BW is split between all connected aircraft. The maximum modulation available in terms of bits per Hz for this 4G network is 64 Quadrature Amplitude Modulation (64QAM). Note that LTE employs adaptive modulation and coding rate derived based on signal quality represented by signal-to-interference and noise ratio (SINR).

ii) 5G DA2GC network

The 5G DA2GC network characterizes future wireless network based on LTE with advanced techniques toward the 5G network, such as antenna arrays enabling coordinated beamsteering, multi-user MU-MIMO, and higher order modulations. Particularly, the coordinated beamsteering technique enables to set antenna pattern and maximum antenna gain in direction of served aircraft while minimizing interference toward other aircraft. Together with MU-MIMO, where a high number of antennas is employed in DA2G-eNB, one DA2G-eNB is able to serve more aircraft simultaneously. Moreover, each aircraft can have its own dedicated beam with full BW. This enables Space Division Multiple Access (SDMA). SDMA allows reaching higher network capacity available for each aircraft. Moreover, the specific environment with ensured LOS between DA2G-eNBs and aircraft and antennas with higher gain allows using higher order modulations, such as 256QAM. We assume to exploit the 14 GHz band for the 5G DA2GC network as suggested in [11].

iii) Satellite communication network

To provide a more comprehensive analysis of potential solutions, we also assess the performance of A2G connection provided via satellites. In this study, the satellite connection is represented by the link between an aircraft and an LEO satellite which is located 1500 km above the ground level, using the carrier frequency of 100 GHz [8]. Main advantages of satellites located in LEO in comparison with satellites in GEO (35786 km) are significantly lower communication delay (20 ms for LEO in comparison with 250 ms for GEO [8]) and higher capacity available per user. Since LEO satellites have narrower beam coverage area, each satellite beam serves a lower number of users. For this reason, LEO satellites provide higher throughputs compared with GEO satellites.

Since the satellites are located in LEO, their orbital speed needs to be higher than earth rotation to stay in the same orbit. Because of higher speed and since Europe covers only 2% of earth surface, each particular satellite stays above the Europe around 10 minutes maximally. For example, around 1000 satellites in total are needed around earth to ensure minimally 20 satellites simultaneously above Europe. In the case of 200 satellites above Europe, 10000 satellites are required in LEO, which exceeds the number of satellites of all planned projects together [9].

For SC, the high antenna gain is typically used on both communication sides, i.e. satellite and aircraft. As in the case of 5G DA2GC, 256QAM and MU-MIMO (represented by spot beam technology in SC) are employed. For the sake of

simplicity, we assess only the communication link between satellite and aircraft. The link between satellite and ground station is not considered in this analysis. For this link, we assume a dedicated channel with enough capacity.

B) Simulation settings

The performance of A2G connections is assessed in static link budget analysis and in dynamic simulations. Static link budget analysis shows edge capacity reachable by one aircraft while dynamic performance comparison evaluates the influence of other aircraft in a dynamic environment with moving aircraft.

i) Static simulation

The link budget calculations describe the static case of the A2G network. For both 4G based and 5G based DA2GC networks, two cases, the best and worst cases, are examined. The worst case represents an aircraft placed at a cell edge, equidistant to three DA2G-eNBs (one serving and two interfering). Considered inter-site distance (ISD) between two DA2G-eNBs is equal to 200 km, which means the longest distance between aircraft and DA2G-eNBs is around 115 km. In the best case, the aircraft is placed directly above the serving DA2G-eNB where the distance is only 10 km. For SC in link budget calculations, we consider 200 satellites above Europe.

ii) Dynamic simulation

In dynamic simulations, the influence of aircraft movements on available SINR and capacity is assessed by using our aircraft mobility model. For deeper comparison, ISDs and a different number of satellites are taken into account. The deployment of DA2G-eNBs is assumed as always hexagonal and uniform with the same ISD for the whole Europe. The deployment and movement of satellites are random with uniform distribution.

Parameters of the dynamic model, as well as wireless channel, are listed in Table I and Table II.

TABLE I. List of simulation parameters.

Parameter	Value
Max altitude of aircraft	43000 feets (13.1 km)
Average climb time	1500 s
Variance of climb time	75 s
Average descent time	1800 s
Variance of descent time	90 s
Number of take-offs	20 starts/minute
Total length of simulation	2 hours
Number of background aircraft (always present)	10
MIMO	2x2 (polarization diver.)
Thermal Noise PSD	-174 dBm/Hz
Beamforming gain	5 dB
Coordinated beamsteering gain	20 dB [14]
Number of symbols/ms	168
LTE modulation	from QPSK to 256QAM (2 – 8 bits/symbol)
LTE overhead (for all links)	25%
Inter-site distance (ISD)	40 – 200 km
Total number of DA2G-eNBs	300 – 7500
Total number of satellites	1000 – 10000
Number of satellites above Europe	20 – 200

V. RESULTS

In this section, numerical results for the analysis of 4G and 5G DA2GC and of SC are presented. In the first subsection, static link budget analysis is calculated while second and third subsection shows dynamic performance comparison.

A) Static link budget calculations

Table 2 introduces detailed link budget calculations. As expected, the highest PL is exhibited by SC. In comparison with DA2GC networks, the difference is nearly 40 dB. This is caused by the combination of higher frequency band and longer distance between transmitting and receiving antennas, which mainly influence PL , as stated in (1). However, thanks to higher antenna gain in the case of SC, experienced signal-to-noise ratio (SNR) is comparable with the cell edge cases of DA2GC networks.

If interference and noise are taken into account, the SC shows lower SINR than the 5G DA2GC network but higher SINR than the 4G DA2GC network in cell center. The reason for low SINR of the 4G DA2GC network is low transmitting antenna gain and mainly interference caused by close DA2G-eNBs. The highest theoretical Shannon capacity of ~ 109 Mb/s holds for the 5G DA2GC network in cell center with BW of 20 MHz. The 4G DA2GC network exhibits the lowest available capacity at the cell edge.

By employing LTE network with 2x2 MIMO and adaptive modulation and coding rate, the maximum capacity for 5G DA2GC network and SC is the same, equal to ~ 187 Mb/s. The equality is caused by maximum modulation, which is 256QAM in both cases. It means that even if the 5G DA2GC network is able to provide a SINR of nearly 43 dB in the cell center, 256QAM is not capable to fully exploit SINR higher than 28 dB [15]. In other words, if SINR is higher than 28 dB, the highest modulation and coding scheme with the maximal efficiency is always selected and thus no improvement in capacity can be seen for SINR levels higher than 28 dB. The

solution could be to employ an even higher-order modulation scheme, which can help to improve maximum capacity. On the other hand, 4G DA2GC network can achieve only ~ 140 Mb/s and ~ 22 Mb/s in cell center and at the cell edge, respectively. Due to high interference at the cell edge, the 4G DA2GC network has the lowest capacity results. In addition, the peak capacity is limited due to maximum modulation, which is only 64QAM.

Note that these results are valid only for one static aircraft served by one antenna. The evaluation of the total available capacity for one aircraft in the dynamic environment is the objective of the following subsections.

B) DA2GC capacity analysis under dynamic scenario: 4G vs. 5G

In this subsection, the dynamic performance analysis of 4G and 5G DA2GC networks is provided. The results of simulations are shown in Fig. 2.

The subplots of Fig. 2 show the distribution for experienced SINR and experienced capacity over flight duration for 4G and 5G DA2GC network, respectively. In other words, the depicted curves show percentage of time spent by aircraft experiencing at least a given SINR or capacity. Curves express complementary cumulative distribution function (CCDF). As can be seen in the Fig. 2(a), the experienced SINR is nearly the same regardless of ISD for single DA2GC network. The difference between 4G and 5G based DA2GC networks is given mainly by coordinated beamsteering employed in the 5G DA2GC network. Results show that aircraft employing 4G DA2GC network can guarantee at least 2.5 dB SINR for 95% of flight time while aircraft using 5G DA2GC network can have SINR 17.5 dB or better for 95% of flight time. The 5G network allows fully exploiting higher modulation schemes and reaching higher capacity.

Fig. 2(b) indicates maximum available capacity per aircraft. As expected, a lower ISD means higher available capacity per

TABLE II. Static link budget analysis.

Parameters	4G network		5G network		SC [8]
	Cell center	Cell edge	Cell center	Cell edge	–
Transmit power [dBm]	45				30
Tx and Rx antenna distance [km]	10	115	10	115	1 500
Frequency band [GHz]	3.4		14		100
Bandwidth [MHz]	20				
Propagation loss [dB]	123.07	144.28	135.36	156.75	195.96
Tx antenna gain [dBi]	20		30		53
Rx antenna gain [dBi]	10				53
Received power [dBm]	-48.07	-69.28	-50.36	-71.58	-59.96
Noise [dBm]	-100.99				
SNR [dB]	52.92	31.71	50.63	29.41	41.03
Interference + noise [dBm]	-76.07	-71.27	-92.68	-88.32	-89.62
SINR [dB]	28.00	1.99	42.32	16.75	29.66
Shannon maximum capacity [Mb/s]	97.16	31.56	108.74	82.99	98.77
Shannon spectral efficiency [b/s/Hz]	4.86	1.58	5.44	4.15	4.94
Used LTE-type modulation	64QAM	QPSK	256QAM	64QAM	256QAM
Used LTE-type coding rate	948/1024	449/1024	948/1024	772/1024	948/1024
LTE-type capacity (2x2 MIMO) [Mb/s]	139.86	22.10	186.73	113.99	186.73
LTE-type spectral efficiency [b/s/Hz]	6.99	1.11	9.34	5.70	9.34

Fig. 2. (a) Maximal average SINR and (b) capacity experienced by aircraft over flight duration for 4G and 5G DA2GC networks.

aircraft for both networks. Although positions of deployed DA2G-eNBs are the same for each ISD-curve for both networks, the 5G DA2GC network significantly outperforms the 4G DA2GC network for all settings. The higher capacity of the 5G DA2GC network is given mainly by employing MU-MIMO, which enables SDMA. It allows to serve nearly each aircraft by its own signal beam and thus to exploit full BW. In the case of the 4G DA2GC network, each DA2G-eNBs has only three sectors and all aircraft connected to the same antenna have to share the same resources. Therefore, in the case of ISD equal to 200 km, the capacity is larger than 130 Mb/s for nearly 50% of flight time if the 5G DA2GC network is employed. On the contrary, in the case of the 4G DA2GC network with the same ISD, aircraft spent 50% of flight time with a guaranteed capacity of about 16 Mb/s or better.

C) Comparison of DA2GC and satellite communication under dynamic scenario

This section compares the performance of 5G DA2GC network and SC. As in the previous case, subplots of Fig. 3 depict maximal experienced SINR and maximal experienced capacity over flight duration for 5G DA2GC network and for SC, respectively.

As first Fig. 3(a) shows, SINR experienced by aircraft connected via SC is higher than in the case of DA2GC for more than 95% of flight time. This is especially due to the higher gain of transmitting and receiving antennas. DA2GC

can attain higher SINR only in the case of the short distance between a DA2G-eNB and an aircraft.

However, as Fig. 3(b) shows, 5G DA2GC outperforms SC in total capacity available for one aircraft. The main reason is the distance between satellites and aircraft. Although we assume antennas with very high gain and with MU-MIMO (spot beam technology) on satellites, the width of beam close to the ground is always higher than the width of a beam produced by 5G DA2GC network antennas due to the distance. It results in more aircraft placed in the same beam and need to share the same resources. As the results show, even if there are 200 satellites placed above Europe (i.e. 10000 globally), 50% of flight time is at maximum capacity of only ~40 Mb/s.

VI. CONCLUSION

In this paper, we analyze the capacity limitation of direct air-to-ground communication (DA2GC) networks based on 4G and 5G technology and of air-to-ground communication provided by satellites. Besides numerical and simulative analyses, this paper outlines also a set of challenges toward DA2GC. The highest capacity is achieved by the 5G DA2GC network, mainly by coordinated beamsteering in combination with MU-MIMO. Aircraft connected to 5G DA2GC network experience more than 130 Mb/s for nearly 50% of flight time if 200 km inter-site distance and 20 MHz bandwidth are exploited. Conversely, the DA2GC network based on 4G suffers from interference, which significantly limits the signal quality and thus the total available capacity. Therefore, only

Fig. 3. (a) Maximal average SINR and (b) capacity experienced by aircraft over flight duration for 5G DA2GC network and satellite communication.

16 Mb/s is available for 50% of flight time if the same setting is employed. In the case of satellite communication, although satellites provide the high-quality signal link, the capacity is divided among more aircraft. It results in the reduction of capacity available for one aircraft, reaching maximally 40 Mb/s for 50% of flight time, even if 10000 satellites are employed globally.

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