3G, HSPA and 4G LTE Network Reliability and Achievable Internet Speeds on Airborne Aircraft up to 10.000 ft Above Ground Level

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Keywords: aeronautical data link, 3G network, HSPA WCDMA network, 4G LTE network, ACARS, CPDLC, NAVTEX, Internet-based data link, general aviation

Received: November 13, 2022

Nowadays, we are witnesses of 5G mobile technology advancements and many countries plan to or already have introduced this technology to public usage. However, the older technologies such as 3G, HSPA and 4G LTE, because of their physical properties, ways of datagram transfers and frequency bands used, are still very suitable for usage in cases that assume longer distances between terminal device and cell towers. Having that in mind, research was conducted during 2021. and 2022. in order to test i.e., verify or refute the hypothesis that 3G, HSPA and 4G LTE technologies will be reliable enough to provide a satisfactory connection on aircraft flying up to 3 km (10.000 ft) above ground level, quality enough to establish Internet connection speeds of at least 1Mbps, which would be enough to serve as a medium for innovated, Internet-based data links similar to CPDLC/ACARS. Through a series of 14 airplane flights, both above plains and mountain regions, first-hand data was gathered and analyzed accordingly, so reliable conclusions about presented hypothesis could be made. Empirical research results were accompanied with research results made on well-known computer radio propagation simulator TAP7.

Povzetek: Raziskava je ugotavljala zanesljivost omrežij v 3G, HSPA in 4G LTE tehnologijah na letalih do 3 km nadmorske višine.

1 Introduction

Before planning any data collection and analysis activity, it is important to precisely determine which values will be measured and how, and what do they represent. In this paper, the main focus will be on analysis of 3G, HSPA WCDMA and 4G LTE technologies performance in conditions of flying aircraft, with maximum flying altitudes of 3 km (10.000 ft) AGL (above ground level), where cell towers are standard fixed ground stations and remote nodes are devices in aircraft. Aside from network quality indicators, great attention will be made towards achievable Internet speeds and ping times.

3G technology uses electromagnetic spectrum in radio wave section, with frequencies in range from 800 to 2100 MHz. HSPA WCDMA technology uses also radio waves on frequencies from 850 to 2100 MHz. More precisely, HSPA uses only one of these frequencis at a time: 850 MHz, 900 MHz, 1700 MHz, 1900 MHz and 2100 MHz. 4G LTE connection standard uses radio waves in frequency range all from 450 up to 5900 MHz, but frequencies in between are not used freely: there is a list of several allowed usage frequencies from mentioned range, like for HSPA, and these frequencies are 450 MHz, 600 MHz, 700 MHz, 800 MHz, 850 MHz, 1500 MHz, 1600 MHz, 1700 MHz, 1900 MHz, 2000 MHz, 2100 MHz, 2300 MHz, 2400 MHz, 2500 MHz, 2600 MHz, 3500 MHz, 3600 MHz, 3700 MHz, 5200 MHz, 5800 MHz and 5900 MHz.

3G services allow a regular user to have an Internet speed of at least 7.2 Mbps, but in reality, the speed of 3G services can only reach up to a maximum of 3 Mbps. For HSPA WCDMA technology, theoretical speeds, with maximum signal strength, should be around 14 Mbps, while in reality most of the times this speed will vary from 5-6 to 10 Mbps.

4G LTE technology, as a much greater improvement with regard to 3G and HSPA, should support Internet speeds of up to 150 Mbps in ideal conditions, but average values, measured by portal Commsbrief.com, indicate that real-world speeds are mainly in range from 15 Mbps to 25 Mbps.

The aim of this paper is to determine whether mentioned technologies, or at least some of them, can provide reliable Internet speed of at least 1Mbps in airborne aircraft, which would represent a good base for further development of digital aeronautical data transfer links and communications systems, in order to replace slow HF and VHF data links used for ACARS, NAVTEX and CPDLC.

2 Related works and SOTA

Internet access started to appear on aircraft in the last 20 years. Boeing was a pioneer in this field - it began to offer internet access in 2001 through a service called 'Connexion'. It expanded commercially from 2004 with a number of international airlines, but was abandoned in 2006 - partly due to its weight of nearly 450kg.

Gogo, one of the leading providers of inflight internet today, began internet service in 2008. Early inflight internet systems were based on low bandwidth satellite communications. As such, they were very slow and expensive ([15], [6]).

Today, inflight internet can be provided by two different ways – via satellite and via ground-based stations. As there were recorded attempts to install and maintain dedicated ground infrastructure solely for internet services in aircraft (like described in [15] or [14]), these attempts failed mainly because of great maintenance costs and general unprofitability of the concept.

However, the approach of using regular cellular networks, even with a bit older technology like 3G, was not analyzed enough in our opinion. There were attempts, like described in [16] and [17], to make 5G internet connection in aircraft, by using regular cell towers on the ground, but this approach still turnes out as very unreliable. Even theoretically, 5G-based internet connection can cover only low altitude airspace, above greater urban areas and with much degraded performace of the network – mainly because of pure physical properties of 5G signal. This means that only above cities/towns with installed 5G equipment inflight internet would work, and with no guaranteed performance, which is not satisfactory.

There are somehow noticeable tendencies to try to solve certain problems – inflight internet being one of them – only with newer and newer technologies, forgetting that maybe the solution in currently present but not yet put to use. Maybe older technologies for data transfer, like 3G and HSPA, could make a great fit in this still volatile and unreliable field of inflight internet. If some of these technologies turn out to be reliable enough, they could possibly be used as a medium for more serious purposes, like direct data links with flight crew and real-time flight data transfers (aside from, or in addition to currently used ADS-B or ADS-C, or newly introduced FANS-1/A). There is no evidence that 3G, HSPA and LTE bands are adequately analyzed from the angle of usage for providing inflight internet (for available info see [6], [8] or [13]).

Having that in mind, the main aim of this paper is to fill the gap and practically test performances of 3G, HSPA and LTE networks in aircraft flying up to 10.000 ft, which is the portion of airspace where most general aviation flights are conducted.

Results yielded from this formal, scientific approach and underlying empirical research can give valuable insights and information needed for planning the future of inflight internet and its spreading to the greatest possible extent, by finding ways to greatly optimize maintenance costs with, at the same time, guaranteed levels of service quality and reliability.

3 Research preparation

For this research, the following equipment has been provided:

- one mobile phone Samsung A70, model SM-A705FN/DS;
- one mobile phone Lenovo C2 L10A40;
- one mobile phone Samsung J5 2017;
- one 3G/HSPA/EDGE/GPRS/GSM USB modem Huawei E220;
- one 3G/HSPA+/EDGE/GPRS/GSM USB modem ZTE MF667;
- one mini computer Raspberry Pi 4 model B (2019), with operating system CentOS 7.

Above mentioned radio-enabled devices have these technical characteristics:

1. mobile phone Samsung A70, model SM-A705FN/DS: chipset Qualcomm SDM675 Snapdragon 675 (11 nm), with 8-core processor consisting of 2 cores Kryo 460 Gold (Cortex-A76) at 2000 MHz and 6 cores Kryo 460 Silver (Cortex-A55) at 1700 MHz), with these basic connectivity characteristics: GSM: 850 / 900 / 1800 / 1900; WCDMA: B1, 2, 5, 8: LTE band 1 (2100), 3 (1800), 5 (850), 7 (2600), 8 (900), 20 (800), 38 (2600), 40 (2300), 41 (2500);
2. mobile phone Lenovo C2 L10A40: Quad-core 1.0 GHz Cortex-A53 processor with Mediatek MT6735P chip; operating system Android 6.0; with these basic connectivity characteristics: GSM 850 / 900 / 1800 / 1900; HSDPA 850 / 900 / 1900 / 2100; LTE band 1 (2100), 3 (1800), 5 (850), 7 (2600), 8 (900), 20 (800), 38 (2600), 40 (2300), 41 (2500);
3. mobile phone Samsung J5 2017: Octa-core 1.6 GHz Cortex-A53 processor with Exynos 7870 Octa (14 nm) chipset; operating system Android 7.0; with these basic connectivity characteristics: GSM 850 / 900 / 1800 / 1900; HSDPA 850 / 900 / 1900 / 2100; LTE band 1 (2100), 3 (1800), 5 (850), 7 (2600), 8 (900), 20 (800), 40 (2300);
4. modem Huawei E220: connectivity characteristics: EDGE/GPRS/GSM 850/900/1800/1900 MHz; HSPA/UMTS (2100 MHz); HSDPA download up to 3,6 Mbps and HSDPA upload up to 384 Kbit/s;
5. modem ZTE MF667: connectivity characteristics: HSPA+/HSUPA/HSDPA/UMTS 2100/850 MHz EDGE/GPRS/GSM 850/900/1800/1900MHz; baud rate mode HSPA+ DL up to 21,6Mbps and HSPA+ UL up to 5.76Mbps; rate mode EDGE/GPRS up to 236 Kbit/s.

As a part of research preparations, a terrain assessment was made, in order to make sure that all types of terrain are included in this research – plain regions, hills and mountainous regions. The plan was to conduct real flights in Serbian airspace, and to make simulated ones over territories of Greece and Denver (State of Colorado – USA), because of great financial and time expenses real flights would represent.

4 Data collection

Mentioned 14 airplane flights were conducted, with all the necessary permissions, in the period from June 10th, 2021 to May 31st, 2022. Flights were conducted in both VMC (visual meteorological conditions) and IMC (instrument meteorological conditions).

Aircraft used for flight conductions were:

- three airplanes Piper PA38-112 Tomahawk;
- one airplane Cessna F172M.

For the flights conducted in VMC, maximum altitude was 2,43 km (8.000 ft) AGL (above ground level). For the flights conducted in IMC, maximum reaching altitude was 10.000 ft AGL.

In the Table 1 some basic information about conducted flights are given.

Flights were conducted in various parts of Serbia, with flight paths aimed to cover greater i.e. broader areas in each flight. Departing airports were LYBJ (Lisičji jarak), LYNS (Čenej) and LYNI (Niš), airports where touch-and-go procedures had been conducted were LYZR (Ečka) and LYSU (Subotica - Bikovo) and destination airports were LYBJ (Lisičji jarak), LYNS (Čenej) and LYSU (Subotica - Bikovo).

For example, on the Image 1 a path of the longest flight i.e. flight number 5 is given. Takeoff and landing airport is LYBJ, with touch-and-go on the LYSU. The flight was conducted in July 2021.

During flights listed in the Table 1, key parameters of cellular networks were tracked and recorded every three seconds, in order to analyze them later.

These parameters were RSRQ (Reference Signal Received Quality, for HSPA WCDMA and 4G LTE networks), EC/IO (Downlink carrier-to-interference ratio, denoting signal quality, in dB, for 2G, 3G and LTE networks), RSSI (Received Signal Strength Indication, denoting signal power, in dBm, for 2G, 3G and LTE networks), ARFCN (Absolute Radio-Frequency Channel Number, for all GSM networks), RSSNR (Signal to Noise Ratio), Active frequencies, neigboring cell towers, approximate distance to serving cell tower, GPS coordinates, current ground speed, altitude and heading.

The accepted refference values for key network parameters such as RSSI, RSCP and EC/IO are given in Tables 2 - 5, and these will be of great importance at research results evaluation.

Besides network physical parameters mentioned above, the measurements included ping times and average download and upload speeds for every 10 seconds interval.

Servers used for pinging were Google's server located in the United States, with public static IP address 8.8.8.8 (further referred to as Server 1), one private server located in Belgrade, Serbia, with public static IP address 194.146.56.151 (Server 2), and one private server located in Sweden, with public static IP address 46.246.29.69 (Server 3).

For data transfer speed measurements, a random package with size of 5 Mb each were used repeatedly i.e. continuously during the flights, in order to estimate average download and upload speeds. Tests for upload and download were active one at a time, which means that bandwidth was not divided between download and upload portions of connection.

It is important to note two things here.

The first one is that antennas of devices used for this research were at all times inside the aircraft, due to effective air traffic regulations, based on which no unapproved device should be attached on aircraft flying, as well as due to device designs themselves. This fact will be further discussed in results interpretations.

The second one is the fact that ground cell towers were regular cell towers used by mobile network. There were no any additional ground stations, for example, on the routes of flying, than those set up by telecom companies in Serbia (which are MTS (Telekom), A1 and Yettel (former Telenor)).

In addition, during the planning phase of this research, a question regarding signal degradation due to Doppler effect arised, because airplanes' great speeds.

More specifically, during this research, airplanes flew at airspeeds not exceeding recommended 110 knots (about 56 m/s) for level flight on Piper PA38 Tomahawk, and 130 knots (about 67 m/s) for level flight on Cessna F172M aircraft, which are generally low speeds for airplanes. Jet airplanes can develop up to 335 m/s ground speeds (as ground speed of airplane is not the same as its airspeed, because of possible significant wind corrections; ground speed can be less than or greater than airplanes' true airspeed).

However, by making calculations on Doppler shift effect for frequencies used by 3G, HSPA WCDMA and LTE bands, by well-known formula

$$f = f_0\left(\frac{c+v_x}{c+v_y}\right)$$

where f is the received wave frequency, f_0 is the source frequency at the transmitter, c is the velocity of radio waves in the medium, v_x is the velocity of the receiver with respect to the medium and v_y is the velocity of the source with respect to the medium, by taking into account that radio wave propagation speed is equal to the speed of light and assuming that maximum possible speed achievable by subsonic airplane is 1200 km/h (approximately 335 m/s), it is easy to conclude that Doppler shift in this case is almost negligible.

Table 2: RSSI 3G and HSPA WCDMA recommended reference values.

RSSI value	Signal quality	Description
>= -65 dBm	Excellent	Strong signal with maximum data speeds
-65 dBm to -95 dBm	Good	Strong signal with good data speeds
-95 dBm to -105 dBm	Fair	Fair but useful, fast and reliable data speeds may be attained, but marginal data with drop-outs is possible
< -105 dBm	Poor	Significant performance drop
-110 dBm	No signal	Disconnection

Table 3: RSSI LTE recommended reference values.

RSSI value	Signal strength	Description
> -65 dBm	Excellent	Strong signal with maximum data speeds
-65 dBm to -80 dBm	Good	Strong signal with good data speeds
-80 dBm to -100 dBm	Fair	Fair but useful, fast and reliable data speeds may be attained, but marginal data with drop-outs is possible
-100 dBm to -105 dBm	Poor	Significant performance drop
<= -110 dBm	No signal	Disconnection

Table 4: RSRQ recommended reference values.

RSRQ value	Signal quality	Description
>= -10 dB	Excellent	Strong signal with maximum data speeds
-10 dB to -15 dB	Good	Strong signal with good data speeds
-15 dB to -20 dB	Fair to poor	Reliable data speeds may be attained, but marginal data with drop-outs is possible. When this value gets close to -20, performance will drop drastically
<= -20 dB	No signal	Disconnection

Table 5: EC/IO recommended reference values.

EC/IO value	Signal quality	Description
0 to -6	Excellent	Strong signal with maximum data speeds
-7 to -10	Good	Strong signal with good data speeds
-11 to -20	Fair to poor	Reliable data speeds may be attained, but marginal data with drop-outs is possible. When this value gets close to -20, performance will drop drastically

Furthermore, knowing also that 3G, HSPA and 4G cellular technologies have their own effective error correction algorithms implemented, and can easily endure smaller changes in operating frequency, it is even more clear that Doppler shift in this case will not be a thing that on any significant way affects performance or reliability of connection.

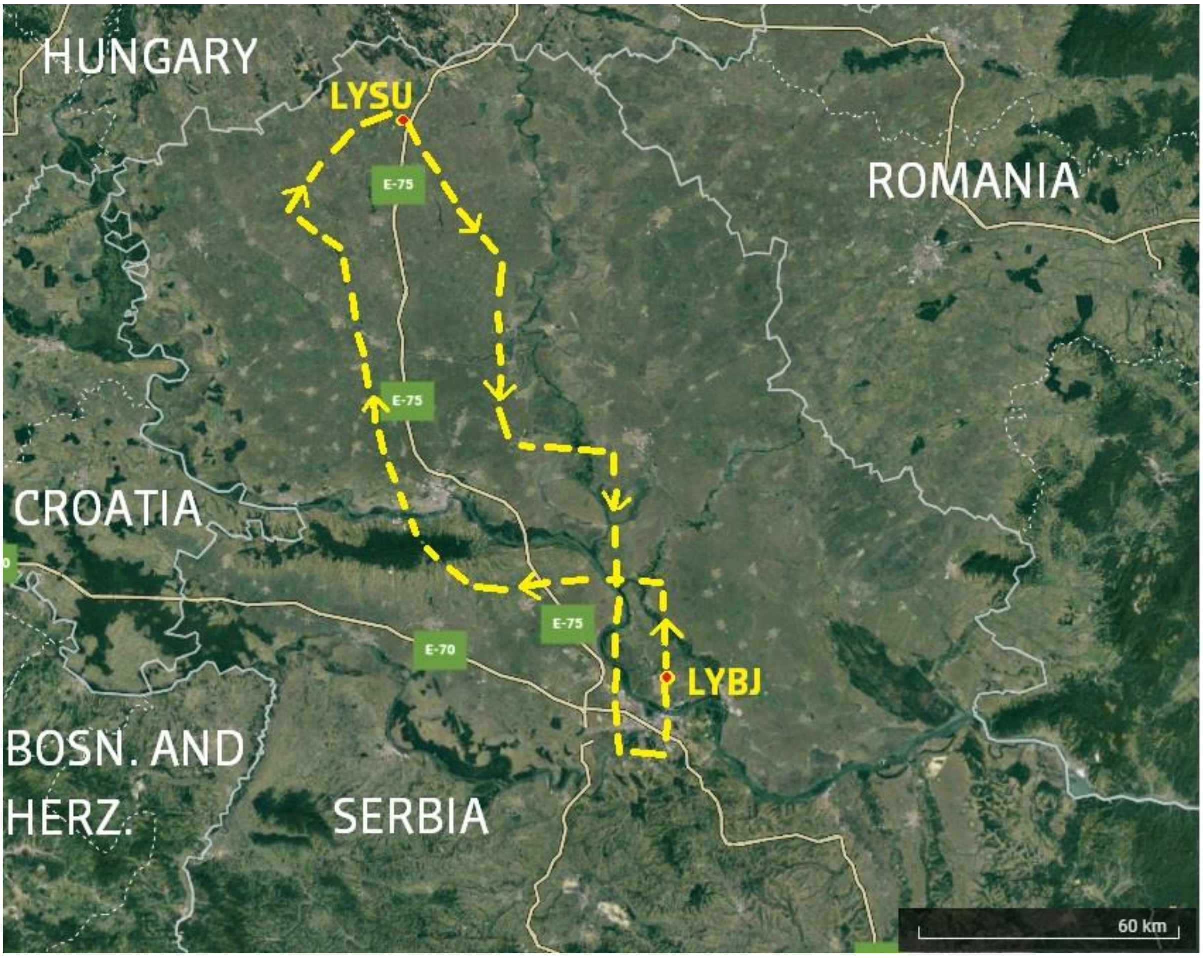

Image 1: An approximate flight path of the flight number 5.

5 Verification and refinement of collected data

Data verification phase was conducted simultaneously with data collection phase, in order to speed up the whole process and refine collected data. During this phase, measurements gathered during airplane taxiing, lineup and holdings on the ground were excluded from the analysis, as these measurements do not contain any usable information for intentions of this research.

Taxiing speeds on the groung do not usually exceed 5 m/s, so with these speeds and the fact that airplane is still on the ground, it can be assumed with certainty that usual behavior of cellular network will occur and connection will be undisturbed. However, in order to be sure, additional active frequencies checks were conducted. As a result, there was no evidence that usual airplane instrumentation, or communication frequencies used by air traffic control units, will on any way interfere with cellular networks of this paper's interest, whose frequencies are already very different than those used in aviation.

This information is also very important during the actual flight, in order to make sure that the readings gathered by cellular equipment are correct and not subject to noticeable noise levels that potential airplane/navigation/communication devices could cause.

Furthermore, collected data was refined in a way that it was split in several categories, based on meteorological conditions that were present during the recording sessions i.e., flights. These categories are

Category VMC – visual meteorological conditions, and

Category IMC – instrument meteorological conditions, with these subcategories: SF – surface fog; R – rain; CL – flight through clouds.

Data was also split in subcategories based on current airplane altitude, so there were 10 additional categories:

Subcategory 1 – altitudes from 0 m to 300 m (0 ft to 1.000 ft)

Subcategory 2 – altitudes from 300 m to 600 m (1.000 ft to 2.000 ft) etc.

Subcategory 10 – altitudes from 2700 m to 3000 m (9.000 ft to 10.000 ft)

With categorization system explained above, data category will be represented and referred to as, for example, VMC.1 - meaning visual meteorological conditions and flight up to an altitude of 300 m (1000 ft), or IMC.SF+R.6, meaning instrument meteorological conditions, with surface fog and rain, and flight between 1500 and 1800 m (5000 to 6000 ft).

6 Data analysis

Based on data gathered from Serbian Regulatory Agency for Electronic Communications and Postal Services (RAECPS), in 2021 there was a general 3G/4G coverage research conducted over the territory of Serbia. Knowing details about their achieved results will have a great impact on evaluation of data gathered in research conducted in-flight, because a lot of network parameters, once airborne, depend on current state on the ground in the means of ground stations density, power, supported technologies and carriers (as mentioned, in Serbia there are three of them).

In February 2022., RAECPS published coverage maps for 3G and 4G/LTE networks in Serbia (RAECPS, 2022), as well as coverage graphs shown on Image 2 and Image 3. Notice that readings are relevant only for the close proximity to the ground, as research was conducted only on the ground, by both the moving and stationary equipment.

As can be concluded based on mentioned coverage maps, cellular network over Serbia can be assumed very uniform – there are no greater areas without coverage or with poor signal coverage. Places with recorded poor network parameters are mostly places on high mountains or regions with grean litospheric deviations, which all impacts networks when observed from the ground. However, flight is very different because there are no direct or indirect obstacles for signal to travel, so it was expected that there would not be overflown areas without coverage or with poor signal quality.

This expectation, as further noticed in this paper, can be seen as correct based on the results gathered in flights over these areas. For the sake of duration of this paper, and better understanding of data processings made, summarized key results and findings will be given. As there were no recorded overflown areas without network coverage or with coverage that can be considered

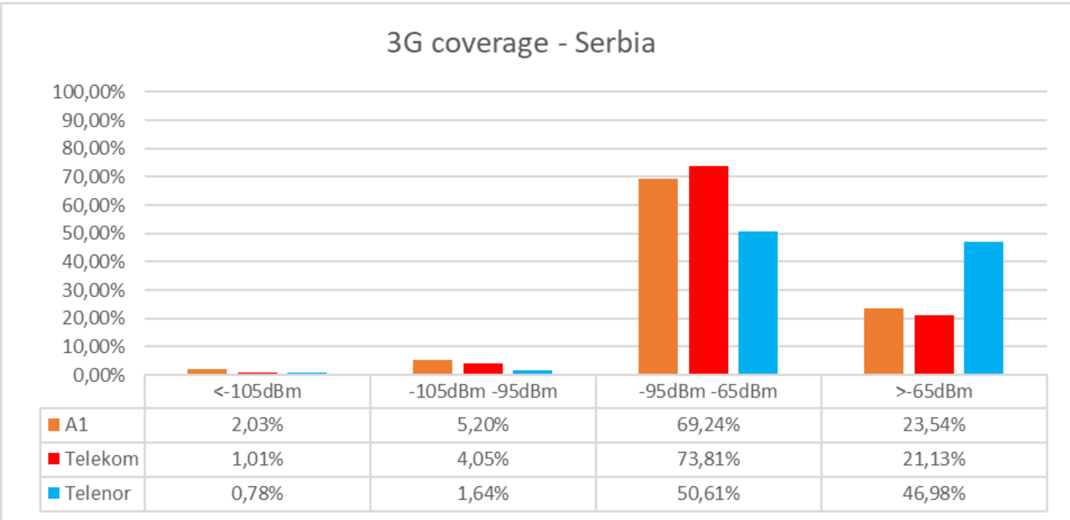

Image 2: Serbia 3G coverage overview for 2021 – all three available carriers.

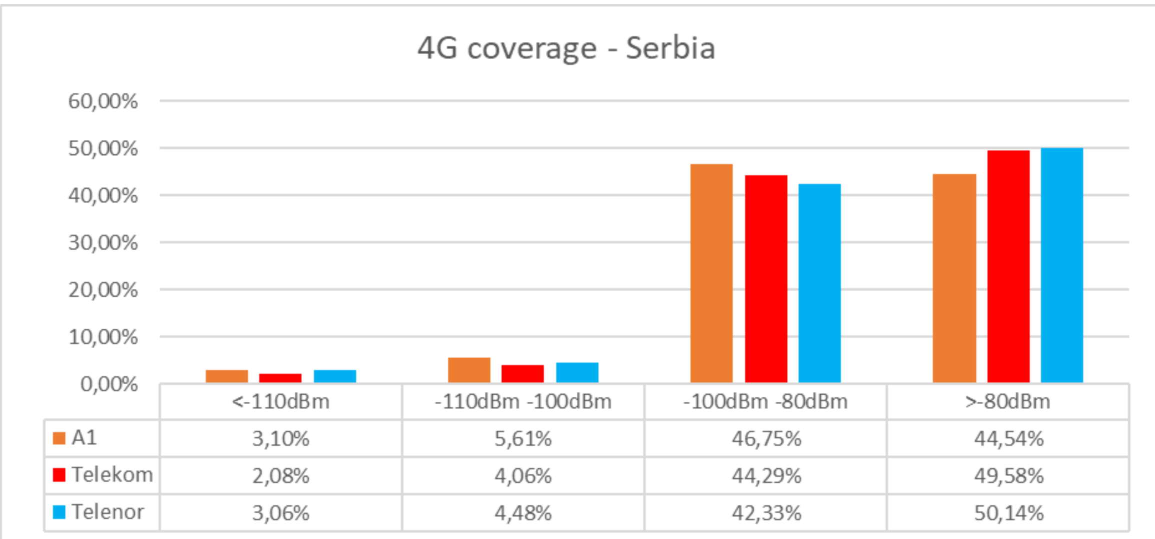

Image 3: Serbia 4G coverage overview for 2021 – all three available carriers.

Table 6: Visual meteorological conditions – categories VMC.1 to VMC.8

Category	Mean LTE RSSI [dBm]	Mean 3G RSSI [dBm]	Mean LTE RSRQ [dB]	Mean 3G RSRQ [dB]	Mean EC/IO	Mean ping [ms] Server 1	Mean ping [ms] Server 2	Mean ping [ms] Server 3
VMC.1	-67,05	-64,01	-10,8	-7,9	-6,4	64,18	24,88	67,81
VMC.2	-69,78	-65,74	-11,9	-8,1	-6,99	74,96	25,69	64,31
VMC.3	-69,66	-68,32	-12,2	-8,32	-7,3	87,85	25,65	84,32
VMC.4	-71,95	-68,84	-12,4	-8,47	-9,03	89,8	30,5	89,7
VMC.5	-78,87	-72,98	-12,5	-8,89	-9,62	116,85	44,5	92,9
VMC.6	-85,94	-77,96	-15,7	-10,7	-9,62	133,17	67,85	118,2
VMC.7	-92,78	-81,77	-16,1	-11,9	-11,1	163,9	84,09	124,88
VMC.8	-94,98	-84,87	-16,0	-14,17	-13,4	164,3	99,16	126,45

Table 7: Instrument meteorological conditions – categories IMC.R+CL.1 to IMC.R+CL.10

Category	Mean LTE RSSI [dBm]	Mean 3G RSSI [dBm]	Mean LTE RSRQ [dB]	Mean 3G RSRQ [dB]	Mean EC/IO	Mean ping [ms] Server 1	Mean ping [ms] Server 2	Mean ping [ms] Server 3
IMC.R+CL.1	-72,32	-74,11	-11,2	-8,3	-6,0	89,03	21,14	74,12
IMC.R+CL.2	-77,6	-76,5	-13,3	-8,8	-7,1	94,54	27,74	82,11
IMC.R+CL.3	-78,52	-80,1	-15,2	-8,97	-8,22	99,05	29,85	91,7
IMC.R+CL.4	-86,11	-87,0	-15,4	-8,99	-10,2	101,89	45,14	107,37
IMC.R+CL.5	-94,5	-89,12	-16,7	-10,1	-12,4	104,17	74,55	128,01
IMC.R+CL.6	-99,6	-93,4	-16,5	-12,5	-12,1	164,14	79,15	123,27
IMC.R+CL.7	-112,48	-99,5	-18,7	-17,3	-15,1	195,85	93,55	148,36
IMC.R+CL.8	-116,4	-101,1	-19,6	-18,34	-17,7	208,54	159,79	177,21
IMC.R+CL.9	-118,22	-108,4	-20,2	-18,3	-17,9	242,65	166,93	192,11
IMC.R+CL.10	-119,1	-109,1	-21,2	-18,6	-18,3	266,06	194,45	206,89

inadequate for usages analyzed in this paper, some data will be aggregated and only their mean values displayed, for each of categories mentioned before.

Having that in mind, obtained data on network parameters are published in Table 6, Table 7 and Table 8. Results given in mentioned tables are mean results for all of the three telecommunications carriers in Serbia.

When achieved Internet speeds come to interest, the obtained values are shown in the Table 9 and Table 10.

For the end of this chapter, in order to visually represent achieved signal qualities on conducted flights, some characteristic cumulative distribution function (CDF) graphs of RSSI indicator are presented on Image 4 – Image 9, with corresponding explanations below each of them.

Table 8: Instrument meteorological conditions – categories IMC.F.1 to IMC.F.10

Category	Mean LTE RSSI [dBm]	Mean 3G RSSI [dBm]	Mean LTE RSRQ [dB]	Mean 3G RSRQ [dB]	Mean EC/IO	Mean ping [ms] Server 1	Mean ping [ms] Server 2	Mean ping [ms] Server 3
IMC.F.1	-71,12	-71,01	-11,2	-8,1	-6,2	84,11	23,25	77,87
IMC.F.2	-73,2	-71,34	-11,3	-8,2	-7,4	84,52	24,16	74,11
IMC.F.3	-74,96	-76,32	-13,2	-8,52	-7,89	97,11	27,13	78,24
IMC.F.4	-80,18	-82,52	-13,6	-8,76	-9,67	91,41	35,14	94,24
IMC.F.5	-91,1	-81,99	-16,1	-9,52	-10,1	124,16	34,16	98,11
IMC.F.6	-99,0	-88,03	-17,2	-11,1	-10,9	127,14	74,11	113,24
IMC.F.7	-100,23	-91,4	-17,9	-12,1	-13,5	123,14	83,09	121,14
IMC.F.8	-107,41	-97,12	-18,6	-15,12	-14,2	174,52	129,16	130,40
IMC.F.9	-108,79	-101,0	-19,2	-16,7	-17,2	172,61	150,45	147,96
IMC.F.10	-110,7	-102,18	-19,2	-16,6	-17,4	186,2	144,45	186,89

Table 9: Visual meteorological conditions – categories VMC.1 to VMC.8

Category	Mean download 3G [Mbps]	Mean upload 3G [Mbps]	Mean download HSPA [Mbps]	Mean upload HSPA [Mbps]	Mean download LTE [Mbps]	Mean upload LTE [Mbps]
VMC.1	4,42	2,11	8,96	4,12	36,41	11,26
VMC.2	4,16	2,06	8,04	4,52	31,12	9,82
VMC.3	3,12	1,98	7,41	4,01	25,11	8,86
VMC.4	2,41	1,02	6,04	3,12	14,26	6,24
VMC.5	1,96	0,87	4,52	3,27	8,12	3,38
VMC.6	1,89	0,67	3,47	2,88	6,62	3,11
VMC.7	1,21	0,69	3,44	2,78	6,54	2,04
VMC.8	1,24	0,74	3,36	2,41	4,11	1,96

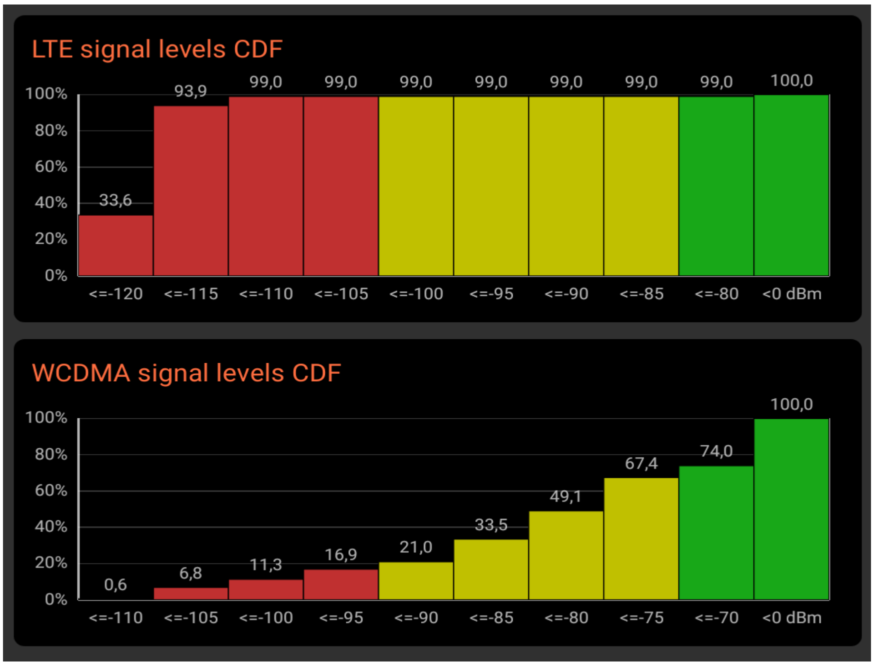

Image 4: LTE and WCDMA RSSI on flight number 6, at altitude range of 8.000ft to 10.000 ft (IMC).

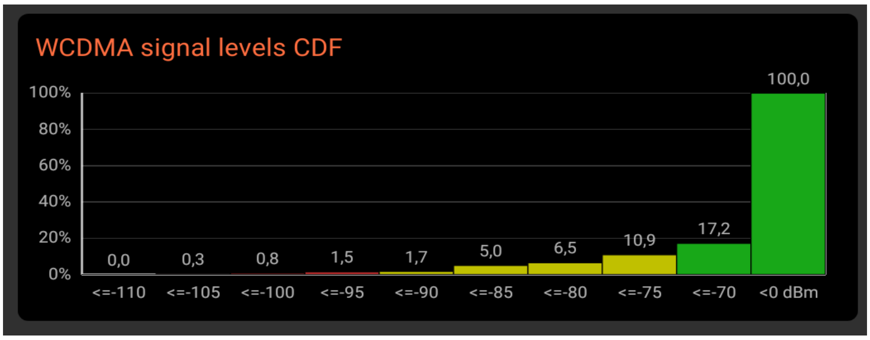

Image 5: WCDMA RSSI on flight number 2, at altitude range of 1.000ft to 3.500 ft (VMC).

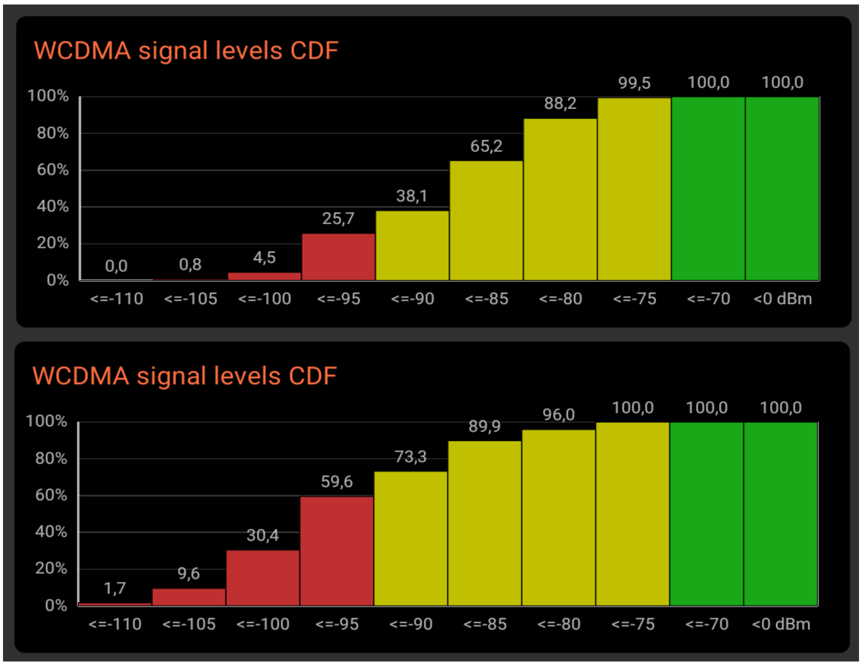

Image 6: WCDMA RSSI on flight number 11, at altitude range of 6.000ft to 8.000 ft (upper graph) and altitude range of 8.000ft to 10.000 ft (lower graph) (IMC).

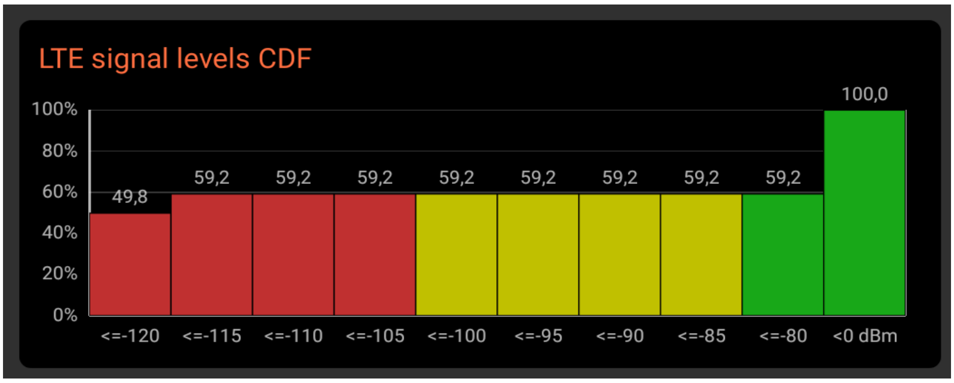

Image 7: LTE RSSI on flight number 12, at altitude range of 2.000ft to 4.000 ft (IMC).

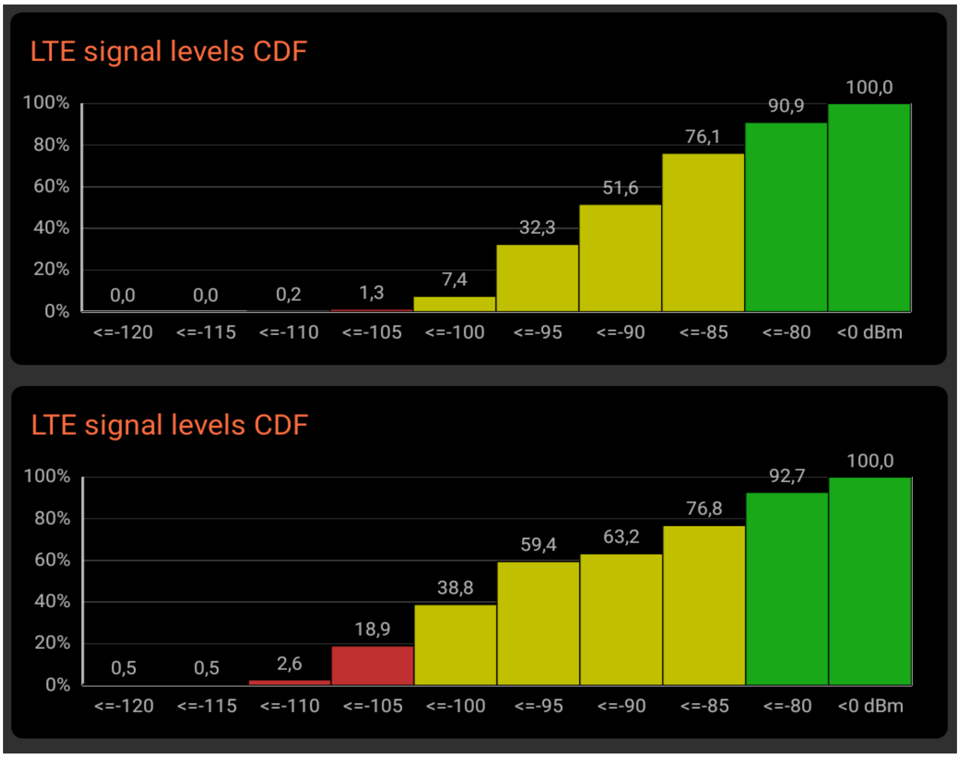

Image 8: LTE RSSI on flight number 4, at altitude range up to 2.000 ft (upper graph) and from 2.000 ft to 3.000 ft (lower graph) (VMC).

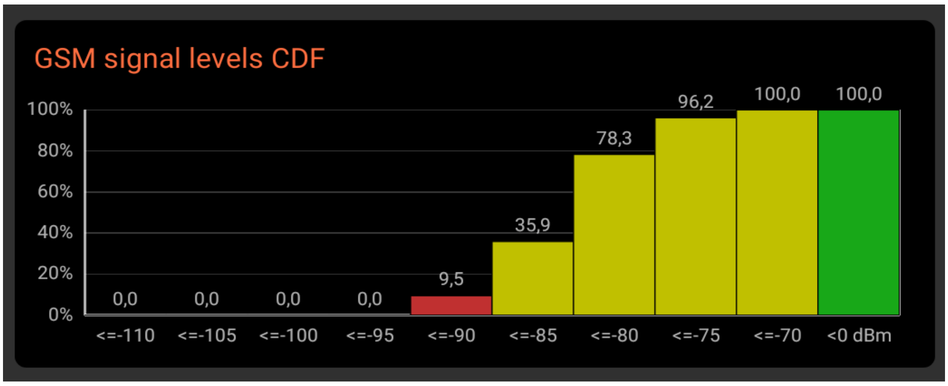

Image 9: GSM RSSI on flight number 6, at altitude range of 8.000 to 10.000 ft (IMC) – this was the worst distribution of RSSI for 2G network in conducted flights (2G network was certainly not in the scope or this paper, but this only represents the fact that 2G networks have much wider coverage possibilities and signal power, as well as more resistance to weather conditions.

7 Conclusions based on empirical research

On the basis of gathered data and presented results, it is obvious that 3G and HSPA WCDMA networks have much greater coverage, greater network connection stability and significantly lower losses of gain due to distance from the ground station, than 4G LTE network. However, 4G network, where available and stable, provides much greater Internet speeds for the lower portion of observed airspace i.e., altitudes up to 5.000 ft (1.516 m).

In the upper portion of airspace (altitudes up to 10.000 ft i.e., 3.000m) the situation changes slightly: it is obvious that HSPA and 3G networks here tend to supply the aircraft with more stable and reliable connection, which can be concluded by looking at achieved Internet speeds and network parameter RSSI (Received Signal Strenth Indication, calculated by formula RSSI = Serving Cell Power + Neighbour Co-Channel Cells Power + Thermal Noise).

When comparing data gathered in VMC and IMC, some noticeable differences catch the eye. These are mainly related to 4G LTE signal strength and quality, as well as achieved Internet speeds – some visible degradations in mentioned parameters in the conditions of rain and flight through clouds are present. These degradations are not very highlighted in cases od 3G and WCDMA network, again proving the assumption that these networks tend to have better performances and lower degradations from moderate to severe weather conditions than LTE (case of heavy rain for example).

As no measurement devices antennas were placed outside the aircraft but were at all times in the cockpit, it is justified to expect that all the results achieved in this research would have probaby been slightly or at least marginally better if collecting devices antennas had been attached to the fuselage of the aircraft from the external side, without any obstacles around them like fuselage walls, aircraft interior, instruments etc.

Furthermore, if the distribution of ground stations were different, it is also justified to expect better results in some of segments analyzed - for example, if ground stations were positioned more often, with radiation pattern different from standard omnidirectional approach (which it suitable for near-the-ground coverage, but not optimized for vertical coverage of airspace).

8 Additional analysis in virtual environment – simulator TAP7

According to the research plan, several simulations in virtual environment had also been conducted. More specifically, simulated events were conducted over the rectangular territory in Greece, because it was a perfect candidate for a territory with great sea-land disunity. The territory itself had these vertice coordinates: 39°22’00’’N 20°24’00’’E, 37°22’00’’N 20°24’00’’E, 37°22’00’’N 22°24’00’’E, 39°22’00’’N 22°24’00’’E (as shown in Image 10). Along with Greece, an additional territory was also analyzed: territory over wider Denver area, with these vertice coordinates: 40°29'03.8"N 103°55'16.2"W, 39°03'14.8"N 103°55'16.2"W, 39°03'14.8"N 106°07'46.5"W, 40°29'03.8"N 106°07'46.5"W.

Transmitters/receivers i.e., ground stations and aircraft were modeled as points in space, on different altitudes, so in program environment it was important to set up the correct altitude and analyze airspace „layer-by-layer "i.e., subcategory 1, subcategory 2 etc. according to flight and airspace categorization mentioned before.

As expected, the higher the altitude – the smaller ammounts of output signal energy from ground stations

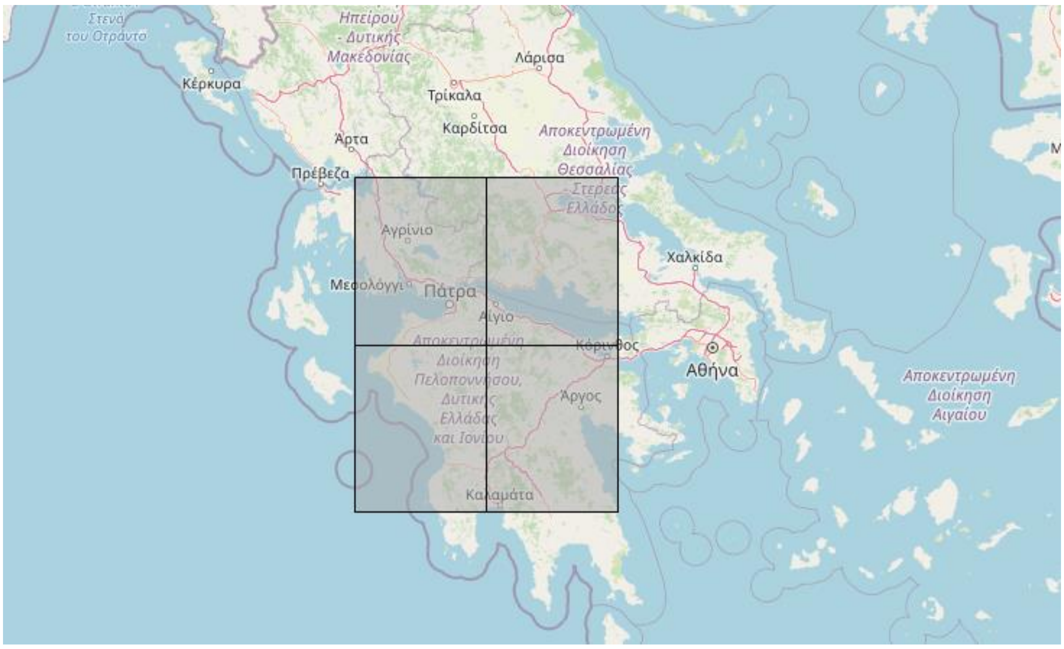

Image 10: Airspace over Greece (grey rectangle) in which program simulations took place.

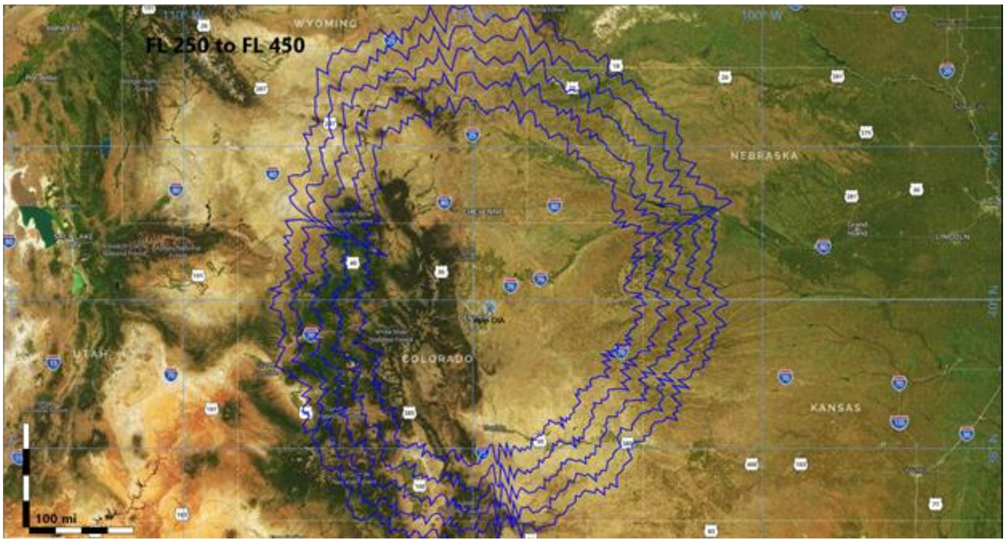

Image 11: An example of Longley-Rice propagation model for imagined 5.4 GHz antenna in the center of the image.

(cell towers) reached airplane, thus limiting the possibilities for Internet connection with higher altitudes.

As there are few known and used radiowave propagation models, in this software simulation the Longley-Rice model has been used: mentioned model is best known for its precision for frequency range between 20Mhz to 20Ghz, which is ideal for appliactions in this research. This model uses statistical resources to compensate for the characterization of the channel, for a telecommunication link, which depends on the variables of each scenario and environment. In other words, this radio propagation model forecasts long-lasting median transmission loss across asymmetrical terrain relative to white-space transmission loss.

This model is mostly used for altitudes not exceeding 3.300m AGL, making it, again, a great choice for analysis of flight altitudes in this research, which are up to 3.000m AGL.

An illustration of Longley-Rice model in TAP 7 program is shown on the Imge 11. In the center of image there is an imagined antenna, and blue lines represent lines with the same predicted effective radio power, rated in dB (isolevel lines). An antenna on the illustration is omnidirectional, so other radio propagation patterns can also be achieved.

During analysis in virtual environment, several possible radio parameters were obtained based on program possibilities: RSCP, RSRP, RSRQ, RSSI, EC/IO.

Based on airspace categorization explained above, mentioned 5 parameters were modeled and recorded for every subcategory. Simulations for clouds and rain, in order to make virtual IMC, were not made because of the program limitations. Hence, output results projected by TAP7 should be accurate in VMC, but degradations in IMC should be expected because of physical properties of carrying signals and theire frequencies.

More precisely, water obstructs radio waves on the frequency bands used by cellular networks. This signal impedance occurs because water drops or vapour in the atmosphere reflects or refracts radio waves. Rainstorms generally tend to have the biggest impact on radio reception because of the density of water vapour associated with them.

However, even the weather can have a direct or indirect impact on 4G (LTE) cellular signal, it shouldn’t noticeably affect cell signals with frequencies under 2GHz (3G channels and HSPA). This was confirmed in a number of researches conducted by physicists and telecommunications companies, as well as here in this research, as described in the previous section.

Having all of the afore mentioned in mind, in the next tables are the results obtained by program TAP7, for VMC categories 1 to 10, with ground stations usual commercial power settings and positioning (covering circle of one cell tower of approximately 4km on the ground). For regions over the sea, cell tower was positioned every 10 km, because here is the situation that unobstructed line of sight is always present between cell tower and client device i.e., aircraft, whose angular speed in referrence to a cell tower is very small).

Table 11: Visual meteorological conditions – categories VMC.1 to VMC.10 – Greece

Category	Mean predicted LTE RSSI [dBm]	Mean predicted 3G RSSI [dBm]	Mean predicted LTE RSRQ [dB]	Mean predicted 3G RSRQ [dB]	Mean predicted EC/IO
VMC.1	-62,2	-61,9	-11,6	-7,74	-8,4
VMC.2	-63,71	-61,7	-11,7	-8,0	-8,7
VMC.3	-66,1	-62,7	-12,8	-8,96	-9,5
VMC.4	-67,2	-62,81	-13,5	-9,74	-9,8
VMC.5	-77,8	-63,91	-13,87	-9,79	-10,1
VMC.6	-72,8	-68,23	-16,41	-11,1	-11,7
VMC.7	-80,7	-72,4	-16,44	-13,29	-11,9
VMC.8	-81,87	-73,2	-16,97	-14,87	-13,1
VMC.9	-83,12	-79,0	-17,5	-14,96	-13,8
VMC.10	-84,11	-81,21	-19,66	-17,55	-13,9

Table 12: Visual meteorological conditions – categories VMC.1 to VMC.10 – Colorado (US)

Category	Mean predicted LTE RSSI [dBm]	Mean predicted 3G RSSI [dBm]	Mean predicted LTE RSRQ [dB]	Mean predicted 3G RSRQ [dB]	Mean predicted EC/IO
VMC.1	-60,1	-58,6	-9,14	-8,41	-6,8
VMC.2	-62,77	-59,55	-9,87	-8,5	-7,1
VMC.3	-63,19	-60,7	-10,13	-8,89	-7,2
VMC.4	-65,55	-61,8	-12,6	-9,77	-7,8
VMC.5	-71,84	-64,2	-12,93	-9,86	-7,8
VMC.6	-77,54	-68,15	-13,4	-10,04	-9,5
VMC.7	-79,52	-72,55	-13,47	-10,38	-12,4
VMC.8	-80,89	-74,25	-14,5	-11,99	-13,1
VMC.9	-81,96	-79,47	-16,85	-14,74	-13,5
VMC.10	-84,41	-80,71	-16,97	-15,55	-14,3

9 Discussion

In the previous chapters, the antenna distribution and radiation patterns were commented. For the latter issue, based on researches coducted earlier, like those by Oguzer, Nosich and Altintas (2004), which were related to radiation patterns of antennas and their achievable gains in dB, the solution could possibly be simple and not very costly. For example, if dish antennas with cone radiation diagrams are used (which would most probably include hyperbolical conductive reflectors made of metal sheets or nets), it should be sufficient to have 8 antennas with radiation cone angle of ~45° and one antenna with radiation cone angle of ~90°: the last one should be pointed directly up to the sky, while 8 others could cover the rest of the airspace (Image 12 and Image 13).

The second remaining task, which should probably be addressed simultaneously with antenna design, is to find the optimal distribution of antennas i.e. cell towers on the ground in order to maximize coverage and signal quality over larger territories. Cell tower distribution could possibly be evaluated in virtual environments, just like here used TAP7. Simulations in these environments are nowadays very precise and can supply the researcher with relevant data and well forecasted results.

These tasks – finding the optimal cell tower distribution on the ground and optimal design - was not evaluated in this research on any way, so that could be an interesting topic for further exploration. The main assignment here would be, obviously, to find the best possible way to successfully cover the airspace with cellular network signal, with the lowest investments possible.

9 Comparations with previous related works in the field

As described in chapter 2, there is no enough evidence that 3G, HSPA and LTE bands were analyzed in a thorough, scientific, empirical way solely from the angle of possible usage for internet connection inflight.

Attempts made were mainly directed towards usage of satellite connection and, lately, for the possible usage of 5G network technology. However, three mentioned technologies, although being a bit old, still have some great potential for being used for longer distances, especially with LOS (line of sight) conditions which are present in scenarios of flying aircraft (as there are no obstacles which would block direct signal travel).

Also, this research tested 3G, HSPA and LTE network behavior on higher altitudes in cases of rain and fog - there is also no evidence that this was conducted before.

Results from this research suggest that especially 3G technology, followed by HSPA on lower altitudes and with LTE in cases of good weather (visual meteorological conditions), are reliable enough to use them as a primary source of internet connection aboard, and to even consider using them for some more advanced applications like real-time data links for exchange of vital flight parameters between ground personnel and floght crews.

10 Conclusions

Cellular network and, in particular, Internet connectivity itself, as well as connection reliability, seems not to be a problem in both real-world and simulated lower airspace environment. During only short periods, mostly when aircraft enters radio shadows or „cones of silence “, as positions directly above ground transmitters are called, disruptions in signal quality should be noticed based on predictions of the TAP7 virtual environment. During actual flights airplanes were not flying directly over base stations but the same effect is expected in the real world, if the antennas are not altered in a way to cover more of the vertical portion of the sky.

This problem, however, could probably be easily solved by installing additional antennas on ground transmitters that are pointed directly towards the sky i.e. which have more cone-shaped radiating pattern, opposite of the omnidirectional antennas with propagation pattern of almost perfect circle. More on this topic was addressed in the discussion section of this paper.

Having in mind achieved rates of data transfer speeds, connection reliability and ping times, along with network quality indicators like RSSI, RSRQ and EC/IO, with a great deal of certainty it can be concluded that usage of 3G, HSPA and/or LTE technologies, for the purpose of Internet connectivity in general aviation aircraft, as well as data transfers between aircraft and air traffic control units or owner company, can be accepted.

The usage of 4G LTE technology, however, mainly because of its physical properties and shorter radio range, can also be suitable but for low-altitude operations such as recreative flying, flight school trainings, crop spraying, firefighting and surveillance purposes. This particularly comes in handy because 4G network provides the possibility to directly transfer real-time image stream from the remote camera to the ground stations, because achievable network speeds are much greater than in 3G networks at altitudes of up to 5.000 ft AGL, as verified by this research.

For the means of possible usages in aeronautical communications, current 3G/4G ground station antenna designs shall be revised, in order to produce maximum possible airspace signal coverage, because near-the-ground coverage is not that essential here – except in the areas and zones close to the airfields and airports.

Based on the main conclusions from this research, with relatively acceptable ammount of investments, in the near future it could be realistic to expect that system similar to current CPDLC, ACARC and possibly NAVTEX can be planned, developed and certified, so data transfers from current HF/VHF radio spectrum can be transferred to 3G, HSPA or LTE bands. There is also a possibility to transfer voice communications over the Internet, so classical radio could remain as a redundant, backup solution in cases of signal loss or system malfunction(s).

Furthermore, if current Internet protocols and technologies get accepted and certified for usage in aviation industry, there is a great opportunity to integrate avionics subsystems of aircraft, air traffic control units, military and/or civil aviation authorities in one autonomous, closed ecosystem, whose backbone would be AFDX-compliant network (Avionics Full Duplex Ethernet) that could physically rely on Internet we know today.

AFDX or other compatible technologes (implementing the standard ARINC 664) are increasingly used on board of many aircraft made nowadays and/or alredy flying, so its expansion outside the aircraft fuselage, by using mentioned wireless radio technologies, would certainly represent a great leap towards more integrated, controllable and safer air traffic.

11 Disclosure statement

The author of this paper declares that he does not have any competing financial, professional, or personal interests from any other party on any way related to this research.

12 Funding

The author of this paper declares that conducted research was financed solely by his personal funds, without third-party grants or financial aids.

References

[1] Ghayas, A. (2020). *Average 4G Speed: How Fast Is 4G LTE Compared To 4G+?*. Internet article. Retrieved on October 5th, 2021 from https://commsbrief.com/average-4g-speed-how-fast-is-4g-lte-compared-to-4g/

[2] GSMA (2019). *Internet of Things Case Study - Telco GSM networks for Low Altitude Airspace Management,* Bulletin, Retrieved July 3rd, 2022 from https://www.gsma.com/iot/wp-content/uploads/2019/08/Drones-Telstra-Case-Study-1.pdf

[3] Longley, A. G., Rice, P. L. (1968). *Prediction of tropospheric radio transmission loss over irregular terrain. A computer method-1968*, ESSA Tech. Rep. ERL 79-ITS 67, U.S. Government Printing Office, Washington, DC (https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/AD676874.xhtml)

[4] Lunden, I. (2013). *European Commission Gives Its OK For In-Plane 3G, 4G Services For Data Use; Airlines Have The Final Say, Though*. Article in online issue TechCrunch, Retrieved July 22nd, 2022 from https://techcrunch.com/2013/11/14/european-commission-gives-its-ok-for-in-plane-3g-4g-services-for-data-use-airlines-have-the-final-say-though/

[5] Johnson, E. E. (1999). *Analysis of Third-Generation HF ALE Technologies.* New Mexico State University, US (http://wireless.nmsu.edu/hf/papers/3g_analysis.pdf)

[6] Mettrop, J. (2006). *GSM On-Board Aircraft.* Aeronautical Communications Panel (ACP), Working Group F – 16th meeting, Montreal, Canada (https://www.icao.int/safety/acp/acpwgf/acp-wg-f-16/acp-wgf16-wp10%20-%20gsm%20onboard%20aircraft.doc)

[7] Oguzer, T. Nosich, A.I, Altintas, A. (2004). *Analysis of an Arbitrary Conic Section Profile Cylindrical Reflector Antenna, H-Polarization Case.* IEEE Transactions on Antennas and Propagation 52(11): 3156 – 3163, DOI:10.1109/TAP.2004.834394 (https://www.researchgate.net/publication/3017809_Analysis_of_an_Arbitrary_Conic_Section_Profile_Cylindrical_Reflector_Antenna_H-Polarization_Case)

[8] Raghavarapu, D. S. N. (2006). *Feasibility study of a WCDMA direct air-to-ground link in the UMTS licensed band.* Karlsruhe University, Germany (https://elib.dlr.de/50627/1/Diplomarbeit_Raghavarapu_Dora_Swamy_Naidu.pdf)

[9] Rice, P. L. et. al. (1967). *Transmission loss predictions for tropospheric communication circuits*. Volume I & II, Tech. Note 101, National Bureau of Standards, US (https://its.ntia.gov/umbraco/surface/download/publication?reportNumber=TN101v1.pdf)

[10] Serbian Regulatory Agency for Electronic Communications and Postal Services – RAECPS (2022). *Radio Coverage.* Website. Retrieved February 21st, 2022 from http://benchmark.ratel.rs/en/radio-coverage-2021

[11] Tait, D., Gillespie, A. F. R., Trinder, S. E. (2012). *Modelling 2G and 3G ALE: A quantitative comparison.* 12th IET International Conference on Ionospheric Radio Systems and Techniques (IRST 2012), DOI: 10.1049/cp.2012.0369 (https://www.researchgate.net/publication/261489689_Modelling_2G_and_3G_ALE_A_quantitative_comparison)

[12] US Department of Defense (1999). *Department of Defense Interface Standard: Interoperability and Performance Standards for Medium and High Frequency Radio Systems - MIL-STD-188-141B,* Whitepaper (http://hflink.com/standards/ALE_standard_188_141B.pdf)

[13] Rusakova, A. A., Tihonenko, D. V. (2016). *Использование сотовой связи и интернета на борту самолета*. Сибирский государственный аэрокосмический университет им. М. Ф. Решетнева, Russia (https://cyberleninka.ru/article/n/ispolzovanie-sotovoy-svyazi-i-interneta-na-bortu-samoleta/viewer)

[14] Perez, S. (2015). *Amazon Video, Music And More Now Available On Majority Of JetBlue's "Fly-Fi" Enabled Planes*. TechCrunch, US. (https://techcrunch.com/2015/11/24/amazon-video-music-and-more-now-available-on-majority-of-jetblues-fly-fi-enabled-planes/?guccounter=1)

[15] Ely, J. (2015). *Electromagnetic Interference to Flight Navigation and Communication Systems: New Strategies in the Age of Wireless.* NASA, US (https://www.researchgate.net/publication/268291731_Electromagnetic_Interference_to_Flight_Navigation_and_Communication_Systems_New_Strategies_in_the_Age_of_Wireless)

[16] Chan, S. (2019*). 5G inflight Wi-Fi is fast approaching*. CISCO, US (https://newsroom.cisco.com/c/r/newsroom/en/us/a/y2019/m10/5g-inflight-wi-fi-is-fast-approaching.html)

[17] Porter, J. (2022). *Inflight 5G calls and data could become a reality in Europe with new decision*. Portal „The Verge" (https://www.theverge.com/2022/11/28/23481637/european-union-inflight-5g-commission-spectrum)