The future of data communication in Aviation 4.0 environment

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Abstract: *Currently experienced the dawn of the Aviation 4.0 era is transforming the contemporary technological environment, throughout the whole aeronautical industry, by creating cyber-physical systems. Following the evolutionary path, incorporating advanced automated and first autonomy systems, the applications involved are becoming increasingly data- oriented. The need for progressive data analytics, massive adoption and operation of IoT devices, delivering advanced monitoring and machine learning opportunities, building the core structure for artificial intelligence, will put a significant pressure on data communication and connectivity itself. In the near future, the problems may especially arise in datalink used in civil aviation. This research paper briefly studies the contemporary systems used for datalink, determines dominant aspects of Aviation 4.0 and their overall impact on the performance requirements of the data communications network, and proposes the possible solution to the problematics, with newly emerging LEO satellite mega-constellations providing Internet connectivity. The conclusion of this paper highlights the requirements for future data communication systems and determines whether the existing and proposed datalink subnetwork technologies are capable of meeting the demands established by Aviation 4.0.*

Key Words: *Aviation 4.0, datalink, SATCOM, in-flight connectivity, Starlink*

1. INTRODUCTION

Exponential growth of technological advancements has placed the aeronautical industry into the new evolutionary era - Aviation 4.0. The influence of Aviation 4.0 ranges from manufacturing, through aircraft operation and air traffic management, to the innovative services for passengers. This paper briefly summarizes my own work *The future of aircraft data communication and management as a part of Aviation 4.0 concept* [1]. As the work [1] implies, the expected rise of connectivity requirements, predominantly from the availability and performance perspective, may cause unwanted problems. Initially, the limited possibilities of current datalink technology, combined with the demand of passengers expecting the same level of Internet access services as available on the ground, resulted in demand for substantial bandwidth and supply gap has been created.

For current flight safety related applications the existing datalink technology may be still adequate, but in the Aviation 4.0 environment, it may prove to be insufficient. Work [1] highlights, that without the appropriate innovative measures, the demand and supply gap will become more apparent, not only affecting the connectivity services for the passengers, as of right now, but also affecting operational, and possibly safety related services in future aircraft systems. The existing plans and roadmaps, mentioned later in this paper, indicate that the shift from the existing OSI model based aeronautical network to IPS (Internet protocol suite) is inevitable and the newly developed datalink technologies will be IP based. One of these, in the work studied technologies, with the potential to be used as a datalink of the future, is the newly emerging low Earth orbit satellite mega constellations. My research is aimed to explore the problematics of aircraft data communication offering the introduction to the topic, and possibly opening the discussion about where are the future of aircraft data communication subnetwork requirements put into the direct correlation with Aviation 4.0 environment.

2. DATA IN AVIATION AND CONTEMPORARY SYSTEMS USED FOR DATA COMMUNICATION

The importance of data is undoubtable for today's world, as it is considered the most valued commodity of the 21st century. The presence of data in aviation is essential. Especially in recent years, because of very notable technological development, massive amounts of data are rapidly increasing over time. As Durak, et al. [2] specify that the continuous growth of number of data sources producing highly dynamic data represents a challenge with consecutive storing, processing and analyzing processes. These so-called "big data" cannot be handled in conventional manner. Big data are directly responsible for numerous problems, as the advanced manned and unmanned aviation systems use the machine-to-machine data intensive communication, particularly when using applications based on advanced automation, or autonomy platforms. Hoarding and availability of big data open the possibility of utilizing the algorithms for machine learning, used in decision -making mechanisms. According to Chunga, et al. [3], the current main use cases of machine learning are, observed in logistics and forecasting. Dou [4] suggests that the big data structure in aviation shall be unified in big data platform to create a common information system. But none of the mentioned would be possible without sufficient connectivity solutions.

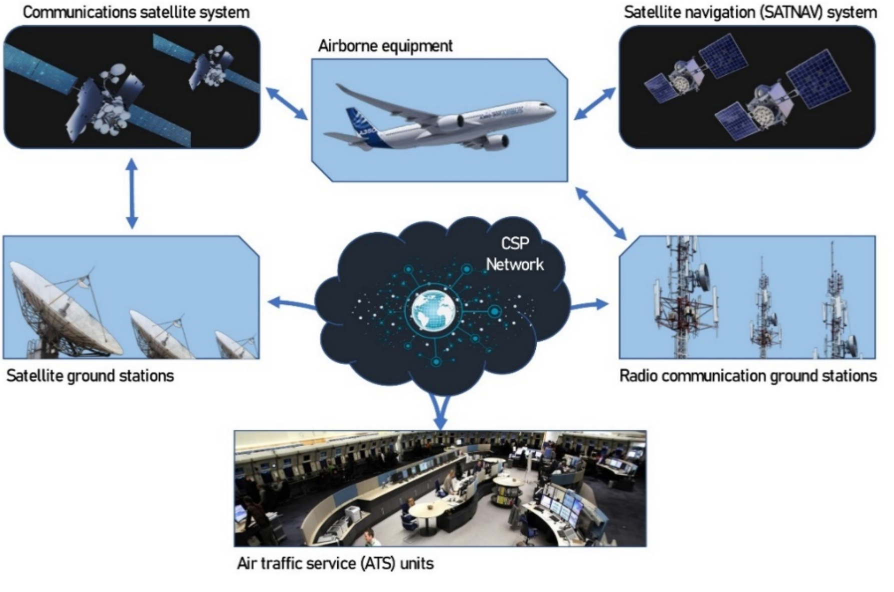

Fig. 1 – Universal overview of a contemporary datalink system

A technologically complicated data communication connectivity solution in aviation is represented by datalink – communication between the air and the ground stations. The main purpose of this type of data communication is the possibility of advantageous capabilities, which are not attainable by the voice communication. Datalink provides more efficient operations, enhanced monitoring and surveillance, and enables space for application and subsequent development of new technologies.

Based on ICAO's Global Operational Data Link Document [5], Fig. 1 shows the universal overview of contemporary datalink system incorporating the base structure of connectivity between the aircraft and the ATS unit. The interconnection between stations is achieved by the use of communication service providers (CSP) networks and the use of satellite communication and/or ground radio communication stations. The satellite navigation system is primarily used for the position data required for airborne equipment, for the purposes of surveillance datalink applications/ data link monitoring applications? The types of datalink systems are represented by given designators of application sets, created by evolution of the datalink communication – ACARS, FANS and ATN Baseline 1 and 2. The systems are defined by used technology – datalink subnetworks, requirements, standards and compatibility features, as defined in [1].

Table 1 shows the summarization of commonly used VHF Datalink and SATCOM datalink technologies together with relatively new systems of AeroMACS and LDACS. To determine the bandwidth capabilities, I have chosen the three type classification of broadband connectivity [1]: 1. *Basic broadband* (throughput 2-30 Mbps); 2. *Next generation access (NGA) broadband* (throughput >30 Mbps, not upgradeable to 1 Gbps - technologically not achievable); 3. *Ultra-fast (UF) broadband* (throughput >100 Mbps, upgradeable to 1 Gbps). The main sources of information [5-9], together with data from official websites of Iridium and Inmarsat were used to create this overview.

Table 1 – Existing datalink subnetworks overview [1]

Datalink Subnetwork	Technical Characteristics	Capabilities & Weaknesses
VDL M2	• Ground based network • VHF band (airband) • 0,0315 Mbps max. data rate per user (theoretical) • Highly variable latency and delay • ACARS, FANS, ATN B1 & B2 compatibility, ATN/IPS applications (planned)	Simple, already deployed subnetwork May be considered as compatible with all current aeronautical communication networks and application sets Simple and low cost needed equipment (antenna similar to voice VHF COMM) Sufficient for current datalink applications
		Very low throughput, significantly below basic broadband speeds Lower quality of connection due to already mentioned lower speeds and highly variable latency and delays Unsuitable for more advanced applications and services requiring better connectivity (higher data rate and latency sensitive applications)

SATCOM Iridium	• Space based network • LEO 66 satellite constellation • SATCOM Class B • L-band (user links), K-band (ISLs, Ground stations) • 0,704 Mbps max. data rate per user • Low/medium latency and delay • ACARS, FANS compatibility, IP services	Truly global availability of Iridium network Sufficient for current datalink applications Relatively small SATCOM antenna Wide variety of offered SATCOM services for aviation including SATVOICE
		The services and applications are offered only to the cockpit and cabin crew terminals – no commercial inflight connectivity for passengers Low throughput, below basic broadband Unsuitable for more advanced applications and services requiring better connectivity (higher data rate)
SATCOM Inmarsat	• Space based network • GEO 4 satellites (I-4 SB) GEO 5 satellites (GX) + 7 more planned • SATCOM Class B (in future possibly Class A) • L-band (SB), K-and Ka-band (GX) • 1,728 Mbps (SB) and 50 Mbps (GX, in future >50Mbps) max. data rate per user • High latency and delay due to geostationary positioning of satellites • ACARS, FANS compatibility + IP services	Almost global availability and coverage Historically first and currently most used SATCOM datalink in aviation Wide variety of offered SATCOM services for aviation including SATVOICE for flight crew With GX satellites, also inflight connectivity for passengers GX satellites enables NGA broadband connection for the aircraft
		No availability of the services for higher North and South latitudes - polar regions (after GX10 deployment, North Pole coverage will be added) The antenna for I-4 SB is relatively small, but K/Ka-band antenna needed to connect to GX network is fairly large creating additional drag for an aircraft Naturally high latency and delay makes this SATCOM not being recommended for the use of real-time and other latency sensitive applications
AeroMACS	• Airport ground based network • C-band • 10 Mbps data rate per user (with 5 MHz channel width) • Low latency and delay	Effective way to create airport connected environment – shared network for airport's fixed and mobile user stations C-band, as practically used for wireless networks in other sectors, it offers good performance characteristics, and it reaches relatively high throughputs IP based network representing trouble-free integration to ATN/IPS

	• IP services, planned to be a part of multilink within ATN/IPS network	C-band is starting to be more congested due to heavy usage in commercial wireless networks (WiFi) and wireless links With the use of only 5 MHz channel width, the throughput covers only basic bandwidth connectivity Need of additional gear and antenna, "only" to be used on the ground at the AeroMACS equipped airport
LDACS	• Ground based network • L-band • Up to 2,6 Mbps data rate per user • Low latency and delay • Planned to be a part of multilink within ATN/IPS network	Very capable, highly scalable ground based datalink subnetwork currently in the process of deployment IP based network representing trouble-free integration to ATN/IPS Possibility of using this datalink subnetwork as a navigational aid, working on the principle of DME
		Very modest data throughput, covering lower limit of basic broadband connection Due to lower throughput, future, high data rate, applications may not be supported

The HF datalink is not included in the overview due to the fact, that both ICAO's Global Air Navigation Plan [10] and SESAR European ATM Master Plan [11] expect its phase out and replacement by SATCOM datalink. With current technological possibilities and overall availability of connectivity services, the ideology of passengers are gradually changing together with demographics. The new emerging generation of passengers, determines the minimum level of connectivity services needed to be offered by airlines in the near future, to satisfy the demands. A 2018 research study conducted by Gogo LLC [12] emphasizes the need for in-flight Internet connectivity availability based on the findings:

- 78% of passengers worldwide want Internet access to be present on board the aircraft.
- 94% of passengers feel that providing this service would improve their flight experience, while 30% of passengers are already looking for Internet on board when booking a flight.
- 92% of passengers indicate an interest in tasks beyond simple web browsing when connected to the Internet - including streaming services, online shopping, tracking of flights and luggage, reservations, etc.
- 63% think that more flights should offer on board WiFi and 48% think that WiFi on an airplane should be as fast as on the ground,
- 92% of "future travelers" are interested in using their own devices on board the aircraft
- 47% would pay for internet connection.

Similarly, the London School of Economics and Political Science, in collaboration with Inmarsat Aviation, has developed an economically oriented study that highlights the benefits of providing an in-flight internet connection service. The most important finding was, that the widespread provision of these services will open a market over time, enabling additional airline ancillary revenue, reaching an estimated 30 billion USD by 2035 [13].

3. AVIATION 4.0 CONCEPT – NOTABLE GROWTH OF DEMANDS ON NETWORK PERFORMANCE

Fig. 2 – Dominant aspects of Aviation 4.0

Regarding the concept of Aviation 4.0, Valdés, et al. [14] offer appropriate and exact explanation of the main revolutionary development stages in aviation throughout the history. The big change presented by Aviation 4.0 lies within the idea of creating the cyber-physical system. This system promises the synergic relationship between computational and physical components. The results of this relationship would be the human assisting, decision making platform, able to operate on certain autonomous level integrating the components of smart aviation systems. As stated in [1], Aviation 4.0 will transform the existing systems into fully digital and smart generation stage. The collected operation data amount and diversity will rise exponentially. Big data acquisition, supervisory control and processing networks will mark the road to the further, and deeper integration of IT systems. Great technological development will enable real-time big data analytics and complex information management with active reaction abilities for decision-making processes. Big data and its analytics may be considered as the corner-stone of Aviation 4.0. Collection of big data is further emphasized by the massive deployment of IoT devices. The volume of created data might seem excessive from the human point of view, even comparing it to the amount created in the past with a noticeably poorer computing power. What we need to recognize, is the necessity of data being made not for human consumption, but for machine learning algorithms of today, to create more robust artificial intelligence structures in the future. Cloud computing helps with the additional storage and processing of data. The use of simulations, creating a “digital twin”, helps with detecting previously unforeseen problems and shortcomings, and provides a possible guideline, leading to improvements. All this is done more efficiently, quickly and mainly safely, than the practical testing of the proposed concepts [1]. Augmented reality offers understandable information interpretation for the users. The meaning of ATM integration lays within the idea of network defragmentation and unification, where information would be efficiently and securely shared among all the interested members, allowing effective and more simplified airspace. Artificial intelligence opens and clears up the way to automation and autonomous systems, which are at the peak of Aviation 4.0 evolution [1]. A very important factor hidden inside each aspect is cybersecurity. Its task is the elimination of potential threads before they do any kind of harm. Cybersecurity in aviation is still one of the most heated topics of discussions regarding the implementation of IPS protocols into aeronautical telecommunications network. Currently, it is difficult to precisely asses the guaranteed level of security with certainty.

4. REQUIRED CHARACTERISTICS FOR FUTURE AVIATION DATALINK SUBNETWORK

Based on mentioned ICAO Global Air Navigation Plan [10], SESAR European ATM Master Plan [11] and overall plans of Future communication infrastructure, the required characteristics and expected requirements of future aviation datalink subnetwork were defined as follows: [1]

- Internet protocol suite (IPS) compatible network using IPv6
- Increased network capabilities in comparison to legacy subnetworks
- Network interoperability features and CNS integration
- Support for both aeronautical data and voice applications (Voice over IP)
- If SATCOM is used, performance class A is required

Fig. 3 portrays an expected development of communication infrastructure roadmap. Blue row contains examples of operational and flight safety related services and applications. In future, fully 4D trajectory based operations will require implementation of advanced ATM services. As mentioned, ATN transformation from OSI based model to IPS will require datalink subnetworks to be compatible with IP. According to [11] main datalink technologies would be IP VDL M2, LDACS, AeroMACS and IP SATCOM, together forming the "Multilink".

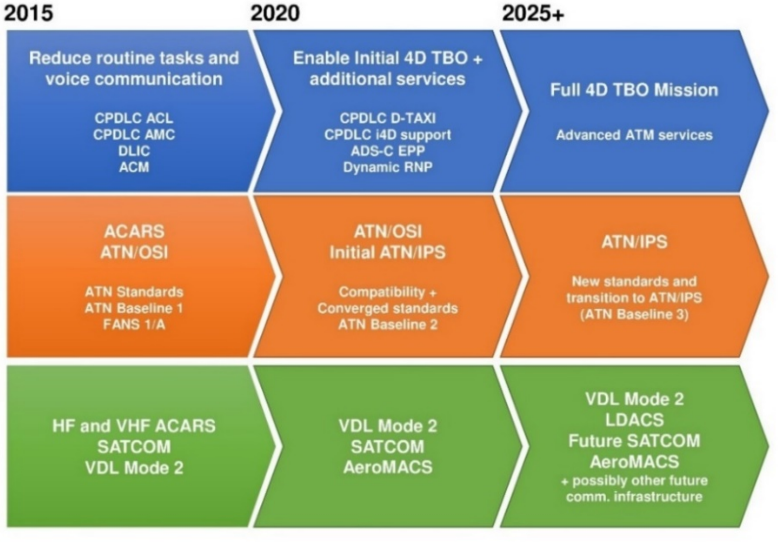

Fig. 3 – Expected simplified development of future communication infrastructure (FCI)

Additionally, as we mentioned the importance of connectivity services provided to passengers, the requirements on datalink from commercial side must be taken into account. The demands include: [1]

- Reliable and secure network divided on the hardware or software level from the network for safety and operational services.
- NGA Broadband connection for connected aircraft as minimum requirement, UF Broadband as recommended requirement + global availability.

After the evaluation of Aviation 4.0 aspects, theoretically stating current and expected characteristics in relation to dependency on connectivity and its performance, Table 2 offers an overview of how each aspect will affect the datalink and what are the main requirements of each aspect on datalink [1].

Table 2 – Main datalink requirements based on Aviation 4.0 dominant aspects [1]

Aviation 4.0 aspect	**How will it affect datalink?** (Air-ground data comm.)	**Main datalink requirements**
Big Data & AI analytics	Streaming of operational data and aircraft condition monitoring	High throughput (with QoS) Low latency (*preferred*)
Cloud computing	Downlink of raw data and uplink of processed data	High throughput Low latency
Advanced cybersecurity	Protection against cyber-attacks and cyberterrorism	High level of network security Secure network comm.
IoT connected aviation	Streaming of data from IoT devices (either already processed or unprocessed)	High throughput (with QoS) Low latency (*preferred*)
Simulations & AR	Uplink/downlink of data needed by onboard computers for simulations	High throughput Low latency
Advanced manufacturing and maintenance	Aircraft condition monitoring, predictive maintenance and AOC	High throughput (with QoS) Low latency (*preferred*)
Integrated ATM	Use of advanced ATM applications for ATS, AOC	High throughput (*preferred*) Low latency (*preferred*) Strictly defined QoS Secure network comm. Global availability (*preferred*)
AI systems & prediction	Extensive machine to machine (M2M) communication	High throughput Low latency Strictly defined QoS Secure network comm. Global availability
Automation and autonomy		

5. LEO MEGA SATELITE CONSTELLATIONS – POSSIBILITY OF NEW IP SATCOM FOR DATALINK

Interest in global Internet connectivity provided by SATCOM may be observed throughout the last 25 years. But only in recent years the technological concepts were starting to appear feasible opening potential multibillion segment.

According to Portillo, et al. [15], as of September 2018, out of 11 LEO satellite mega constellations proposals registered in Federal Communications Commission (FCC), three of them were in advanced stage of development – SpaceX Starlink, OneWeb and Telesat Lightspeed.

Being pointed out in [1], almost 3 years later, because of the current situation and operational maturity of the specified proposals, SpaceX Starlink constellation was chosen for the purpose of this research, to represent the fundamental technological capabilities, which may be applied to a new concept of SATCOM datalink for application in aeronautical industry. Based on initial FCC permission for deploying and operating NGSO satellite system, granted to SpaceX on 28 March 2018, Starlink will operate Ku, Ka and V band LEO and VLEO satellites [1].

After the third modification notice, the initial Starlink constellation will consist of ~12 000 satellites deployed in two phases and SpaceX plans to extend the constellation to its final phase of almost 42 000 satellites [1].

In my work [1], I have determined the Starlink's bandwidth capabilities by gathering 184 speedtest.net results randomly done between July 2020 and February 2021. All of the speedtest.net results were done by the USA customers in areas covered by Starlink, with the standard Starlink equipment.

The found arithmetic mean values of download, upload and latency are *110,34 Mbps, 18,16 Mbps* and *40 ms,* respectively.

Even at the early stages of the satellite deployment phase, Starlink proves that NGA broadband is easily attainable.

Theoretically as Portillo, et al. [15] states in its link budget model, all of the mentioned systems (Lightspeed, OneWeb and Starlink) are technologically capable to hypothetically achieve over 1 Gbps throughput between ground/air station and satellite, so UF broadband Internet access is attainable.

Additionally with the use of Laser inter satellite links (LISL), according to Handley [16], the latency of LEO satellite internet may be in some specific cases significantly lower than conventional ground connection via fiber-optic cables, due to the fact, that speed of light in glass is more than 30% slower, than in near vacuum environment of LEO altitudes, where are the satellites situated [1].

SpaceX submitted two applications to FCC regarding their own experimental testing on board the aircraft. First FCC filling from 7 November 2020, included testing of up to five user terminals mounted in a Gulfstream jets for a period of up to two years. Specifically, operation of one user terminal aboard private jet while on the ground at the airport and in flight over the United State.

In later FCC filling from 5 March 2021, SpaceX requests use of Starlink terminals on "Earth stations in motion" in general, also including Earth stations aboard aircraft (ESAA). This time SpaceX requested testing on U.S. registered aircraft operating worldwide and non-U.S. registered aircraft operating in U.S. airspace.

FCC filling included the paragraph, where SpaceX claims that the testing would serve the public interest and provide high-throughput, low-latency broadband for aircraft. SpaceX mentioned only connectivity services for operator and passengers, not directly referring to datalink [1].

Fig. 4 – Overview of datalink system with the use of proposed LEO IP SATCOM

But, as mentioned in [1] the use of proposed LEO IP SATCOM may truly offer all-in-one solution for datalink. Fig. 4 points out the possible simplification, in contrast to Fig. 1.

The actual network of communication service provider consists of satellite constellation itself, paired with ground stations to maintain connectivity with the ground based Internet network.

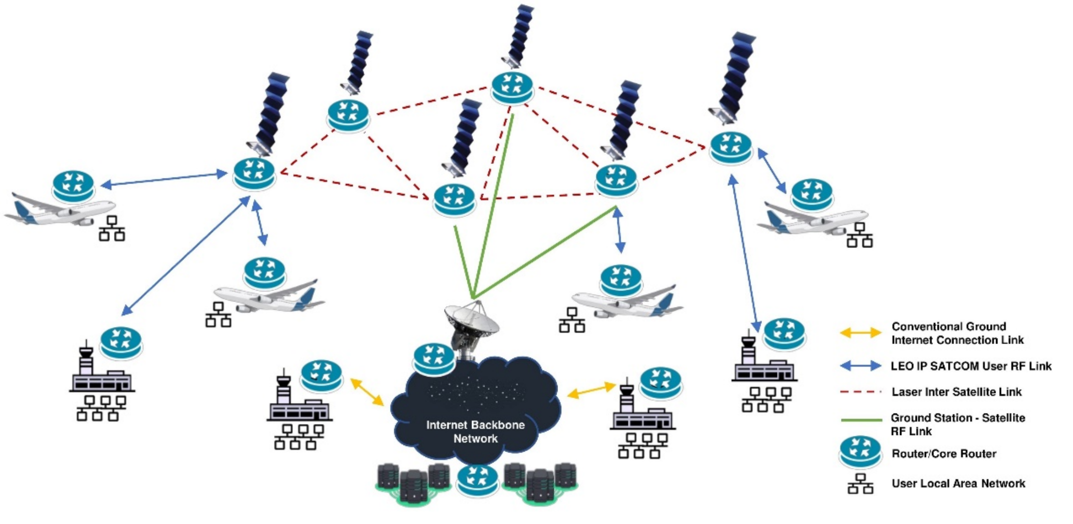

Fig. 5 – Network diagram of proposed LEO IP SATCOM

Fig. 5 shows more detailed network diagram of proposed LEO IP SATCOM, taking into account all proposed technologies, including: inter satellite links, satellites with advanced routing capabilities, sufficient number of ground stations.

The diagram also remarks the ability to globally connect to the Internet network, not only the aircraft, but also airports with insufficient connectivity services, or even remote airports with no Internet connectivity at all [1].

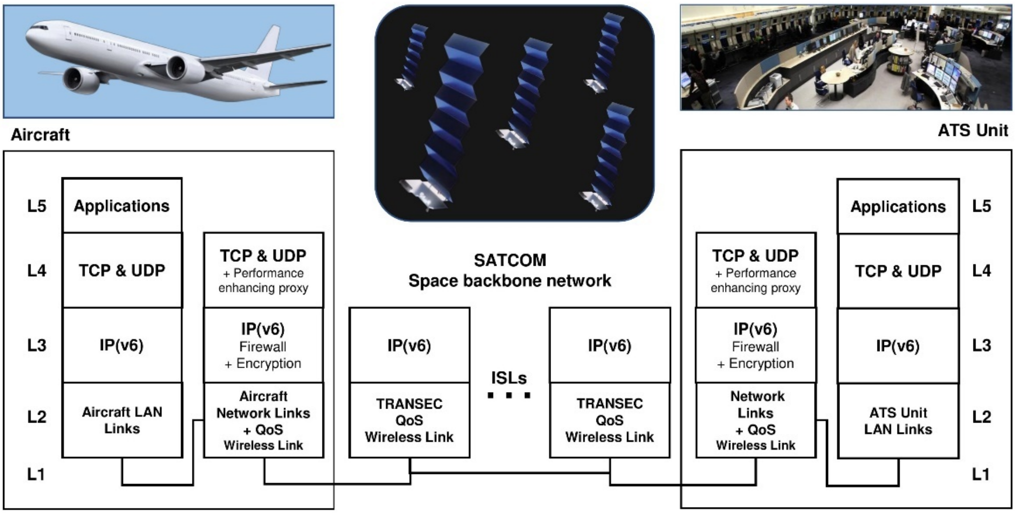

Fig. 6 – ATN/IPS model of LEO IP SATCOM peer-to-peer connection between aircraft and ATS Unit

My work [1] suggests that the communication will be characterized by peer-to-peer connections (see Fig. 6) with the use of IPv6, where it could be easily definable, whether the user is connected directly to the SATCOM network, by simple allocation of defined IPv6 address subnets.

With the functioning inter satellite routing capability, routing of packets, by satellites in constellation, may be based on geographical coordinates.

Due to relatively big coverage of ground by the satellite, the location of the SATCOM terminals does not need to be stunningly precise.

Terminal may, in some form, label the packet with the coordinates describing “where to be delivered”, and the satellites would perform the routing by defying to which next reachable satellite should the packet be forwarded.

Bigger problems arise with terminals in-motion. In this case, the dynamic mobile routing may be applied.

But, especially for aviation, it would be beneficial to store the actual airplanes/terminal geographical positions, with relation to their IP addresses, in a dynamic database. All in-motion terminals/stations would be periodically updating their coordinates and rewriting the data in database.

When contacting SATCOM in-motion terminal with known IP address, the database may be accessed and the corresponding value of geographical coordinates would be used to route the packet.

In my opinion, this operation may work in similar way as DNS resolving process, but with secured access to the database.

By periodical sharing and storing the geographical position of LEO IP SATCOM connected aircraft, we would create the global surveillance database as a possible substitution to the ADS-B surveillance.

The position database may be considered as a part of future System-wide information management (SWIM) network [1].

Table 3 covers, similarly to Table 1, the technical characteristics, capabilities and weaknesses of proposed LEO IP SATCOM similar to the studied Starlink system. The overview includes estimates based on my own research and other previous researches [15, 16].

Table 3 – Proposed LEO IP SATCOM datalink subnetworks overview

Datalink Subnetwork	Technical Characteristics	Capabilities & Weaknesses
Proposed **LEO IP SATCOM**	• Space based network • LEO and VLEO several thousand satellites constellation • SATCOM Class A • Ku-band, Ka-band and V-band + THz EM spectrum for LISLs • Expected >100 Mbps data rate per user • Low/medium latency and delay • IP services, in this thesis projected to be a part of ATN/IPS network and FCI multilink	Truly global coverage and availability of services, from ground to the highest flight level Paired with GNSS, this datalink subnetwork may in the future provide all-in-one solution for CNS, and be primarily used for aeronautical telecommunications Expected throughput of more than 100 Mbps makes this datalink with certainty NGA broadband, even, if the technology will prove possible, UF broadband, with ability to reach more than 1 Gbps Available subnetwork throughput and relatively low latency, will allow easy use of any future datalink applications for the flight crew or aircraft systems (expecting it to be SATCOM Class A) and additionally, inflight connectivity services for passengers may be provided without the need for multiple systems
		Because of used radiofrequencies, the antenna is expected to be complex and also larger in size (adding drag) If not managed properly, very high throughputs per user, may saturate and overwhelm the network within areas of denser grid of connected user terminals Due to gradually increasing use of Ku and Ka-bands, and planned multiple LEO mega constellations using the same frequency spectrum, the RF environment may become highly interfered **Currently, the technology has not yet been commercially used on non-stationary terminals, only experimentally, with publicly unknown results**

6. CONCLUSIONS

The fact that more advanced services and applications used in aeronautical industry are increasingly data intensive when compared to legacy ones, cannot be refuted. Aviation 4.0 environment is starting to set up new level of minimal requirements expected to be met by the future data communication system, including datalink.

Beside the known plans and roadmaps presenting the expected direction of the development, Aviation 4.0, as found by the research [1], would significantly shape the development path and could potentially force the deployment of brand new datalink system, provided that the current ones will not offer any more space for innovation, not being able to fulfill the increasing demands.

The additional important aspect that has to be taken into account, when planning future datalink, besides providing connectivity into the cockpit for safety and operational related applications, is the today's trend of connected cabin with in-flight connectivity services for passengers. According the numerous studies, e.g. [12, 13], the push from the commercial business market is very apparent and the high-quality in-flight connectivity solutions opens up new possibilities of potentially huge additional ancillary revenues for airlines, thus additionally forcing the use and demand for high bandwidth connectivity solution.

In this particular state, the currently used datalink subnetworks are, not able to meet the full spectrum of suggested future characteristics, without the shortcomings (with some subnetworks even substantial) in certain fields [1].

As [1] points out, the proposed LEO IP SATCOM has a theoretical potential to meet all the defined Future communication infrastructure, ICAO Global air navigation plan and SESAR European ATM Master Plan characteristics. One of the biggest advantage of this proposed system, is the potential of using it as all-in-one connectivity solution datalink, being able to handle mandatory safety services including ATC and AOC, as well as other general communications including APC, due to its promising high bandwidth capabilities. But, the possible meeting of general datalink subnetwork characteristics by LEO IP SATCOM are still highly hypothetical, due to the fact, that the use of this technology for commercial aeronautical purposes is either in early experimental, or still only theoretical development stage, with very few sources and researches dealing with this topic. Hence, my estimates of proposed LEO IP SATCOM reaching the future aviation subnetwork is purely theoretically based and only lies within the evidence of capabilities practically tested only on stationary ground terminals. The testing of this technology on board the aircraft in flight is being conducted right now, but the results are still not publicly available.

Despite only hypothetical result, I hope, other researches in the future would continue with this problematics considering commercial LEO satellite mega constellations as a relevant candidate for new datalink subnetwork, or possibly suggesting other potential technologies, using the data communication requirements of Aviation 4.0, from my research.

The importance of data communication should not be overlooked. The actual connectivity, in some cases, directly enables the application and use of advanced technologies, thus the connectivity solution should be given the utmost priority in development.

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