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Aeronautical Networks for In-Flight Connectivity: A Tutorial of the State-of-the-Art and Survey of Research Challenges

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ABSTRACT The aeronautical networks attract the attention of both industry and academia since Internet access during flights turns to the crucial demand from luxury with the evolving technology. This In-Flight Connectivity (IFC) necessity is currently dominated by the satellite connectivity and Air-to-Ground (A2G) network solutions. However, the high installation/equipment cost and latency of the satellite connectivity reduce its efficiency. The A2G networks are utilized through the 4G/5G ground stations deployed on terrestrial areas to solve these satellites' problems. This terrestrial deployment reduces the coverage area of A2G networks, especially for remote flights over the ocean. The Aeronautical Ad-hoc Networks (AANETs) are designed to provide IFC while solving the primary defects of dominating solutions. The AANET is an entirely novel solution under the vehicular networks since it consists of aircraft with ultra-dynamic and unstructured characteristics. These characteristics separate it from the less dynamic Flying Ad-Hoc Networks (FANETs). Therefore, the environmental and mobility effects cause specific challenges for AANETs. This article presents a holistic review of these open AANET challenges by investigating them in data link, network, and transport layers. Before giving the details of these challenges, this article explores the state-of-the-art literature about satellite and A2G networks for IFC. We then give our specific interest to the AANET by investigating its particular characteristics and open research challenges. The main starting point of this study is that there is a lack of compact research on this exciting topic, although IFC is an inevitable need for the aeronautical industry. Also, the AANET could be underlined by giving all state-of-the-art about the dominating IFC solutions. Therefore, this is the first work exploring the state-of-the-art for all the existing aeronautical networking technologies under a single comprehensive survey by deeply analyzing specific characteristics and open research challenges of AANETs. Additionally, the AANET is a novel topic and should be separately investigated from the FANETs as given in current literature.

INDEX TERMS Aeronautical networks, in-flight connectivity, aeronautical ad-hoc networks, air-to-ground networks, satellite connectivity.

I. INTRODUCTION

The number of passengers using aircraft increases gradually over the following years. International Air Transport Association estimates that there will be 8.2 billion aircraft passengers in 2037 [1]. With the increase in the number of passengers, significant changes in their needs have been made. The passengers want to connect to the Internet without interruption regardless of their location and time [2]. Accordingly, passengers want to reach real-time Internet browsing, text messaging, live television, online gaming, and e-mailing during a flight [3]. This situation shows that IFC becomes an essential requirement for passengers during a flight. More specifically, IFC is a critical selection criteria for roughly

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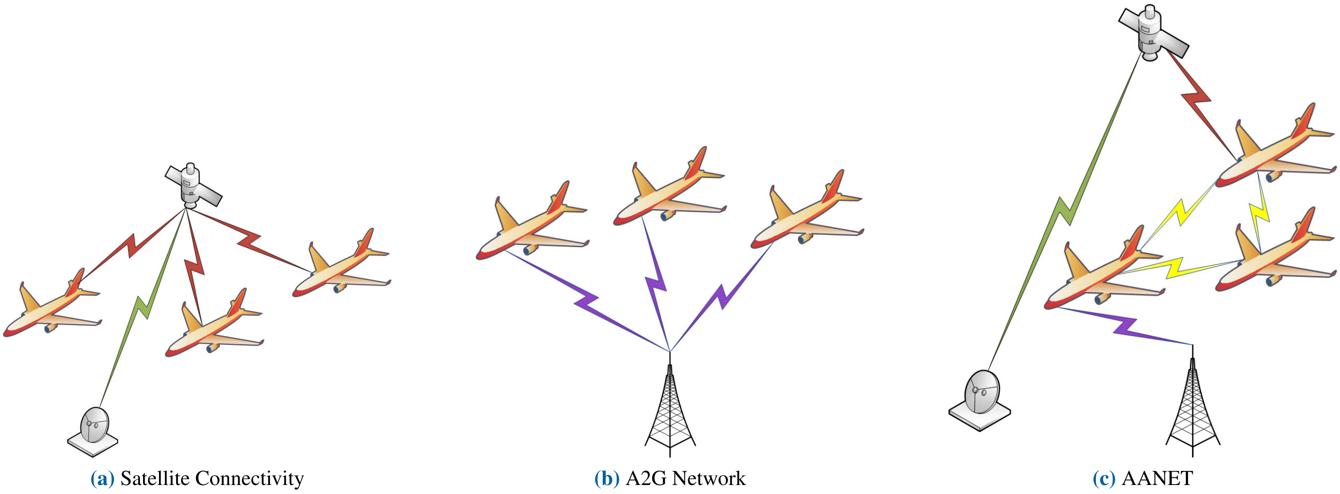

(a) Satellite Connectivity (b) A2G Network (c) AANET

FIGURE 1. **Aeronautical network types for IFC.**

54% of passengers, and they agree to pay extra fees for this service [4]. Also, approximately 75% of passengers are ready to change the airline to get faster and uninterrupted Internet access, while 20% have changed the airline they use [5]. As a result, recently, IFC became a critical income source for the airlines [6], [7]. According to a market report released in 2016, the total revenue obtained from IFC is expected to increase from $700 million in 2015 to nearly $5.4 billion by 2025 with a 23% Compound Annual Growth Rate (CAGR) over the ten years [8]. The number of aircraft that provide this service needs to increase to enable this income. Also, the number of commercial flights is expected to grow from 5300 in 2015 to 23100 in 2025 [9]. More generally, it is expected that IFC will create 130$ billion global markets up to 2035 [10].

Technological advances have made IFC an essential part of the aviation domain. The key figures in the previous paragraph show the importance and popularity of IFC in aviation. This evolving interest leads to more funding and research in IFC by taking the industry and academia's attention. As a result, many publications, products, and projects are in the literature to provide and develop different IFC solutions. Since these solutions and technologies in IFC are not collected under a single study, it takes effort and time to examine them. This situation motivates us to review existing IFC approaches and fill the gaps.

A. SCOPE OF SURVEY

As mentioned, the aeronautical networks and IFC attract the attention of both industry and academia. Accordingly, significant investments and new technologies have come into the aeronautical networking area to enable IFC opportunities in the last years [11]. One of the critical agencies in aeronautical communications is the International Civil Aviation Organization (ICAO), which works to increase the capacity of the global civil aviation system with improved efficiency and safety [12]. More specifically, the ICAO also supports the IFC evolutions by utilizing 5G-based A2G network systems. The other leading organizations in the aeronautical domain are the European Organisation for Safety of Air Navigation (EUROCONTROL) for Europe and Federal Aviation Administration (FAA) for the United States. The standardization of aeronautical radio access technologies is included in the aims of EUROCONTROL, and FAA [13], [14]. These key players divide the aeronautical networks into three categories of satellite connectivity, A2G network, and AANETs as shown in Fig. 1. This survey follows this classification to study existing works in aeronautical networks.

Satellite communication is the oldest method for IFC, and it is also used for aviation control services, which ensure the safety of aircraft [27]. Although the coverage area of the satellite communication is large, the delay and high cost become the main problems for Internet access during the flight. Many ground stations specialized in aeronautical communication are used to provide cellular network service and solve the problems observed in satellite communication. With this A2G network, airplanes can connect to base stations placed in the ground and provide Internet access to their users. However, the ground base implementation of base stations causes coverage issues during remote flights.

To solve the problems of the satellite and A2G networks, by establishing connections between the aircrafts, a temporary air network has been proposed as a new effective technique called AANET. The AANET operates on the principle that one aircraft receives packets from another connected aircraft and routes them to a destination. Due to this ultra-dynamic architecture, the AANET is different from other FANETs under the vehicular networks. More specifically, the AANET experiences distinct challenges in data link, network, and transport layers due to its specific topology and challenges. Correspondingly, in this survey, we give our particular interest to the AANET by explaining its topology, challenges, and open research based on these layers. However, before these, we first investigate the state-of-the-art for the satellite and A2G networks in the IFC. By exploring these aeronautical network technologies, we can highlight the role of AANET in IFC.

1) RELATED WORKS

In literature, various surveys and tutorials are investigating the FANETs concept. A comprehensive study by examining the architecture, the constraints, the mobility models, the routing techniques, and the simulation tools for FANETs are presented in [15]. Similarly, another comprehensive survey for the classification and taxonomy of the position-based routing protocols for FANETs is given in [16]. The general concept, design challenges, and open research issues of the FANETs are investigated in [17]. This work also compares the FANETs with other ad-hoc concepts in literature. The applications of reinforcement learning algorithms to the FANETs under different scenarios are given in [18]. These scenarios include routing protocols, flight trajectory selection, relaying, and charging. Additionally, the mobility models, routing protocols, classification, communication, and application models of the FANETs are surveyed in [19]. The survey investigating the concepts, architecture, applications, routing, simulators, and challenges of the FANETs is also given in [20]. Different from the above-explained works, the existing MAC protocols for FANETs are analyzed in [21]. This work investigates and compares the design issues, operational principles, advantages, and limitations of the current MAC protocols for FANETs. The objectives, challenges, routing metrics, characteristics, open issues, and performance measures of FANETs are comprehensively investigated in [22]. This work analyzes highly dynamic flying nodes' link disconnection and energy consumption problems. The above survey and tutorials explore the FANETs instead of the AANET concept. FANETs consist of less mobile, and low flying nodes compared to the AANETs [23]. These properties make the FANETs less dynamic and unstructured different from aircraft characteristics. Accordingly, the routing concepts, mobility models, and link-layer protocols are different from the AANET. Therefore, the AANET is a novel concept under the vehicular ad-hoc networks, and at that point, it should be separately considered from the FANETs.

In literature, some works are surveying AANET's specific characteristics. The particular interest is given to the AANETs by investigating design characteristics, architectures, routing protocols, and security aspects under the smart city scenario in [24]. Different AANET routing protocols are evaluated with supporting simulation results in [25]. Additionally, although the AANET concept is extensively explained in [26], it only considers the general characteristics of AANET without giving details of other existing IFC solutions.

We believe that there is a need for a comprehensive survey of IFC considering all existing aeronautical networking methodologies. Therefore, we can underline the need for AANETs to readers by explaining aeronautical networking methodologies' problems in the literature. Our main aim is to analyze all the aeronautical networking concepts in detail to enable IFC. According to our investigations, this is the first work to investigate all aeronautical networking methodologies under one comprehensive survey.

B. CONTRIBUTIONS

As explained in the above section, we analyze the leading aeronautical networking solutions for satisfying IFC requirements in this survey. We start this analysis by investigating satellite and A2G networks. We examine essential satellite and A2G-based solutions during this investigation by exploring their advantages and challenges for the IFC domain with their technical details. We then focus on the AANET concept by explaining its topological details, specific challenges, and open research problems. More specifically, we can summarize the main contributions of this survey as follows:

- *Study of aeronautical networks for IFC:* This is the first work collecting all the aeronautical networking types under one comprehensive survey.
- *Identify the satellite and A2G networks by taking advantage of the stat-of-the-art literature:* We explore the main contributions and defects of satellite and A2G network concepts by analyzing their state-of-the-art literature for IFC.
- *Exhaustive analysis of AANET technology:* We give our specific interest to the AANET by investigating its topology, specific challenges, and open research areas in a layered manner.
- *Discuss open research challenges about AANET:* This is the first work identifying AANET specific characteristics, and open research challenges Other works in literature only analyze the topological and technical details of AANETs without investigating their specific characteristics and challenges in a layered aspect.
- *Present a holistic layered review on open research challenges:* We divide open research problems of AANET into layers as data link, network, and transport. Accordingly, we can focus on specific research challenges according to the layer they belong to.

C. ORGANIZATION

The rest of the survey is organized as follows: Section 2 will explain two leading aeronautical network technologies as satellite connectivity and A2G networks by giving their technical background and leading solutions to enable IFC. This section also investigates the satellite-to-air and air-to-ground links. After these, we start to focus on AANET in Section 3, and we first examine the effects of environment and mobility on AANET. The open research challenges for AANETs are analyzed in Section 4 according to a layered concept. Accordingly, we investigate these challenges for the data link, network, and transport layers. In Section 5, we give our future directions. Here, we provide the lessons learned from this article by underlining the remaining challenges and our

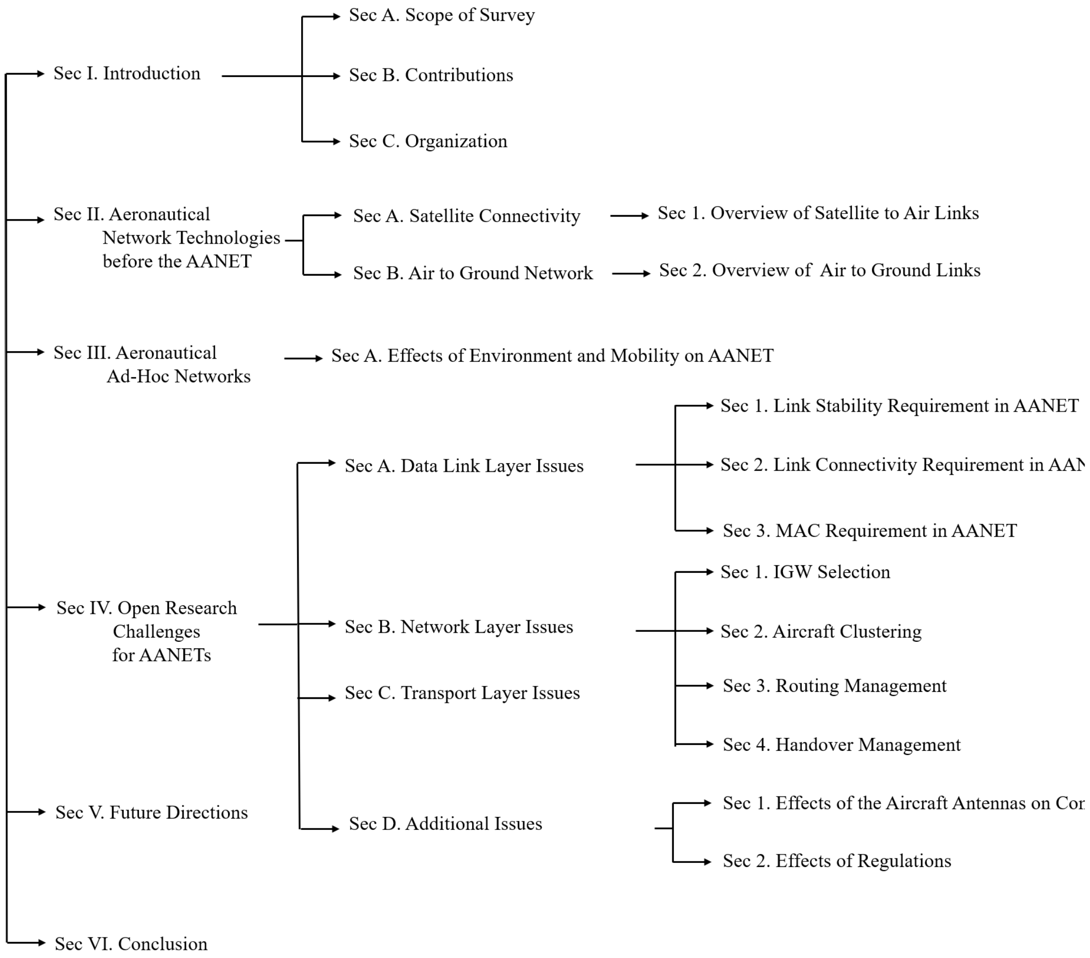


FIGURE 2. Organization chart of survey.

recommendations to overcome them. Finally, we finalize our article by concluding our paper in Section 6.

The detailed organization chart of the survey is also illustrated in Fig. 2.

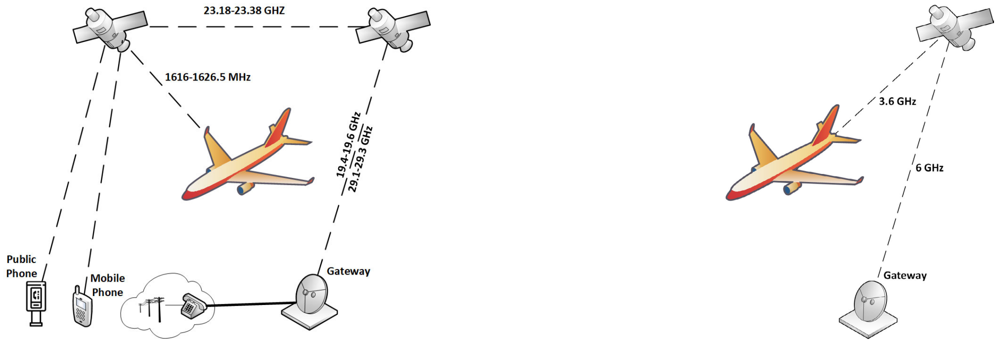
II. AERONAUTICAL NETWORK TECHNOLOGIES BEFORE THE AANET

This section will investigate the two leading aeronautical network technologies: Satellite Connectivity and A2G Network. These aeronautical network technologies exist before the AANET to enable IFC. This section will briefly analyze the advantages and problems of these technologies to show their differences from the AANETs.

A. SATELLITE CONNECTIVITY

Satellite connectivity is the first and most widely used method to enable IFC [28], [29]. The external antenna at the top of the aircraft sends broadband signals to the satellite in satellite connectivity. The satellite transfers these received signals to the ground station after the amplification. The ground station enables data exchange with the Internet, sending signals back to the satellite. Finally, the satellite transfers the data to aircraft through the external antenna again [30]. These procedures to enable IFC are executed through three main types of earth orbit satellites: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO).

1) Low Earth Orbit (LEO): The LEO satellites are located 500-2000 km above ground level. This altitude reduces the latency of LEO satellites, and the Round-Trip-Time (RTT) becomes roughly 30 ms. One of the most common types of LEO satellites is the *Iridium System* that consists of 66 LEO satellites to enable voice and data services. Each satellite can support satellite-to-satellite, satellite-to-gateway, and satellite-to-subscriber links, as illustrated in Fig. 3 [31], [32]. Also, the Iridium System includes two main channels as system overhead (ring alert, broadcast, acquisition, and synchronization channels) and bearer service (traffic and messaging channels) [33].
2) Medium Earth Orbit (MEO): The MEO satellites are located in the 5000-20000 km range above the ground level. For this reason, the delay of the MEO



(a) Overview of Iridium system [28].

(b) Overview of Inmarsat system.

FIGURE 3. **Overview of satellite systems.**

TABLE 1. **Comparison of LEO, MEO, and GEO satellites [37]–[39].**

Parameters	LEO	MEO	GEO
Height	500-2000 km	5000-20000 km	36000 km
Orbital Periods	90 min	2-12 hour	24 hour
RTT	30 ms	100 ms	250 ms
Path Loss	Least	High	Highest
Orbit Type	Circular	Circular	Circular
Handover Number	High	Medium	None
Number of Satellites	40-70	10-12	3
Energy Requirement	Low	Medium	High
Antenna Size	Small	Medium	Large

satellites (100 ms RTT) is higher than the LEO satellites, as shown in Table 1. Also, the coverage of the MEO satellites is higher than the LEO satellites because of their high proximity deployment to ground level. One of the common examples of MEO satellites is the Intermediate Circular Orbit (ICO) system, which consists of 12 active satellites. The ICO can execute voice and data transfers based on the Time Division Multiple Access (TDMA) technology [34].

3) Geostationary Earth Orbit (GEO): The GEO satellites are deployed 36000 km above ground level. This deployment increases the delay of GEO satellites (250 ms RTT) while reducing the throughput of the GEO satellites compared to the LEO satellites [35]. One of the common types of the GEO satellites is the International Maritime Satellite (Inmarsat) system, as illustrated in Fig. 3b. The Inmarsat operates 10 GEO satellites to enable voice and data services to the ground, sea, and air systems. There are three central Inmarsat systems: Inmarsat-2, Inmarsat-3, and Inmarsat-4. More specifically, the Inmarsat-3 and Inmarsat-4 work in the ranges 1525-1559 MHz paired with 1626.5-1660.5 MHz [36]. Moreover, we have many LEO and MEO satellites compared to the GEO. For this reason, we observe an increased number of handovers as shown in Table 1.

The above-explained satellite types are utilized to enable the IFC, and the important satellite-based IFC solutions could be listed as follows:

1) Connexion-by-Boeing: The Connexion-by-Boeing operates in the 14-14.5 GHz frequency band for the mobile platform-to-space links and 11.2 to 12.75 GHz band for the space-to-mobile platform links [40]. These connections achieve 20 Mbit/s and 1 Mbit/s data rates per plane for the downlink and uplink, respectively.
2) SwiftBroadband: It is proposed by the Inmarsat, and the higher bandwidth efficiency of Inmarsat-4 increases the efficiency of SwiftBroadband. The SwiftBroadband allows simultaneous voice and data communication with four simultaneous channels up to 432 kbps for each aircraft [41], [42].
3) Broadband Global Area Network (B-GAN): It enables Internet connectivity by using three Inmarsat-4 satellites that operate the 1626.5-1660.5 MHz frequency range for the uplink and 1525.0-1559.0 MHz for downlink [43]. The data rates for these down- and up-links are roughly 492 kbit/s per plane. Also, the B-GAN can carry out voice calls and data applications simultaneously.
4) Starlink: The more recent satellite solution was developed by the United States Company SpaceX based on LEO [44]. The Starlink is aimed to deploy in three layers with thousands of small LEO satellites. Also, Starlink aims to extend broadband Internet access by enabling an integrated satellite-terrestrial network due to the ground station combination. The stations on the ground exist in two primary forms. Here, the first one is the user access point, while another is related to the operation-control-maintenance access points.
5) OneWeb: The OneWeb is another recent LEO satellite-based solution aiming to enable high-speed Internet and telephony to passengers during a flight. The initial constellation of OneWeb consists of 720 satellites in 18 circular orbital planes at 1,200 km altitude [45]. There are four main links

in OneWeb: gateway-to-satellite, satellite-to-gateway, user terminal-to-satellite, and satellite-to-user terminal. The OneWeb utilized the 10.7-12.7 GHz band for the satellite-to-user terminal links and the 14-14.5 GHz band for the user terminal-to-satellite traffic. Additionally, the 27.5-20.0 GHz bands are used for the gateway-to-satellite links. The satellite-to-gateway traffic generally uses the 17.8-20.2 GHz frequency ranges [46].

In addition to the above-explained three main solutions, different projects and companies propose various techniques for the satellite connectivity domain: *OnAir*, *Row 44*, *ABATE*, *eXConnect*, and GoGo technologies [47]–[49].

1) OVERVIEW OF SATELLITE-TO-AIR LINKS

The above-explained satellite-based solutions utilize the satellite-to-air links to enable IFC. More specifically, the main aim of the satellite-to-air links is to allow communication and data exchange between satellites and aircraft. The transmission method for these links could be selected as Radio Frequency (RF) or optical communication. The main characteristics of these could be listed as follows:

1) RF Communications: The RF is a subset of the electromagnetic spectrum and to execute various aims, it includes different bands: Very Low Frequency (VLF) (3 kHz-30 kHz), Low Frequency (LF) (30 kHz-300 kHz), Medium Frequency (MF) (300 kHz-3 MHz), High Frequency (HF) (3 MHz-30 MHz), Very High Frequency (VHF) (30 MHz-300 MHz), Ultra High Frequency (UHF) (300 MHz-3 GHz), Super High Frequency (SHF) (3 GHz-30 GHz), and Extremely High Frequency (EHF) (30 GHz-300 GHz). The different satellites can use these frequency bands according to their main aim. The satellites could use the VHF, UHF, and SHF bands among the RF frequency bands. The frequencies of the VHF and UHF bands used by the satellites and usage purposes are summarized in Table 2. The higher throughput is provided with the increasing frequency range and reduced antenna size in these bands. For this reason, the current satellite solutions are generally based on higher frequency bands. The higher frequency bands generally enable 70 to 100 Mbps and 2.5 to 30 Mbps data rates to the aircraft and from the aircraft, respectively [50], [51]. However, the high-frequency bands can suffer from the atmospheric attenuation, and free space path loss risk as shown in Table 3 [52].
2) Optical Communication: The optical links could also be used for satellite-to-aircraft communications based on the Line-of-Sight (LOS) concept [55]. The data rate of optical communication is higher due to the reduced antenna size and power, as shown in Table 3 [56]. For this reason, the optical links provide more efficient performance than RF-based communications. Additionally, the optical links could be used for the backbone connections between the aircraft and ground station due to the slow acquisition time [57]. However, the optical links could be affected by the atmospheric effects (absorption, scattering, turbulence, noise, and space loss). This situation can increase the error probability by reducing the received signal quality and link performance [58], [59].

TABLE 2. VHF and UHF bands utilization for satellites [53], [54].

Frequency Range (MHz)	Usage
137-138 VHF	Low data rate satellite-to-earth
145-146 VHF	Amateur satellites
148-150 VHF	Uplink to low data rate satellites
240-270 VHF	Military satellites
399.9-403 UHF	Navigation, positioning, and timing
432-438 UHF	Amateur and Earth resources satellites
460-470 UHF	Meteorological and environmental satellites

TABLE 3. Comparison of RF and optical communication [60], [61].

Parameters	RF	Optical Communication
Wavelength	3 kHZ-300 GHz	300 GHz-3000 THz
Antenna Size	High	Low (1/2 of RF)
Data Rate	Low	High
Communication	Omnidirectional	LOS
Spectrum Restriction	Licensed	Unlicensed
Power consumption	High	Low (1/2 of RF)
Beamwidth	Wide	Narrow
Transmission Window	30 mm-3 m	700 nm-1600 nm
Multipath fading	Medium	Low
Security	Limited	High
Licensing	licensed	Unlicensed

As explained above, the literature includes many IFC solutions utilizing different frequency bands, satellite systems, and satellite-to-air links. However, the long transmission path and high latency could be listed as the primary defects of these satellite-based solutions. Additionally, the higher installation and equipment costs reduce the efficiency of satellite-based systems. The A2G network is proposed as a new IFC method to solve these challenges. In the following subsection, we will give the details of the A2G network by investigating the crucial studies in the literature.

B. AIR-TO-GROUND (A2G) NETWORK

This section will investigate the A2G network by evaluating its main advantages and challenges during IFC. The A2G network takes advantage of the cellular communication model for providing IFC [62]. The specialized ground stations are deployed on the terrestrial areas to utilize mobile telecommunication services and cellular communication. Then, the direct A2G link is established between the aircraft and the closest ground-based cellular station to enable broadband Internet Protocol (IP) connectivity. One or two small antennas should be existed below the fuselage to create these A2G links [63]. After these, the ground station should be determined for connection establishment. Here, the ground stations can send advertisement messages to show their existence, and each aircraft receives advertisements from different ground stations. The aircrafts update their Reachable Ground Station Set table using the accepted advertisements.

In this table, each entry consists of the ground station identifier, advertised prefix, and current minimum hop count to the corresponding ground station parameters [64]. According to this table, the aircraft can select the topologically closest ground station for connectivity. All of the aircrafts connected to the same ground station share the offered capacity of it, and this situation limits the available spectrum, which is one of the main drawbacks for the A2G connectivity as shown in Table 8.

The ground stations in the A2G network could be designed based on the Long Term Evolution (LTE) technology to enable IFC through the A2G concept. The A2G LTE can provide speeds up to 75 Mb/s from the ground station to aircraft and 25 Mb/s from aircraft to ground stations at the 100 km distance and 1200 km/h velocity using 2 × 15 MHz Frequency Division Duplex (FDD). The A2G LTE requires dedicated infrastructure and frequency decoupled from the terrestrial cellular networks. Similarly, the direct A2G link could be established between the aircraft and ground station based on the Time Division LTE (TD-LTE) on VHF band [65]. This deployment obtains 27 Mbps as a maximum downlink speed for the 430 km/h aircraft velocity.

Current LTE technology utilizes beamforming antenna systems. However, the third dimension is required for aeronautical communications through the A2G networks due to they need LOS connectivity. On the other hand, the current antenna technology of the LTE base stations does not satisfy the specific requirements of the aeronautical networks [66]. More specifically, the existing cellular networks could not be sufficient for A2G communications due to the high amount of interference, Doppler shift, handover number, and channel impairments [67]. To solve these problems, the multiple antenna beams are directed to different aerial locations to serve aircraft in [68]. Also, a multi-user beamforming is a methodology to increase the spectrum utilization by creating a separate beam for each aircraft [69]. The multi-user beamforming is also supported by Space Division Multiple Access (SDMA), which can execute simultaneous transmission to spatially separated aircraft. Therefore, the available bandwidth in a single beam could be reused.

Additionally, one of the most significant projects in the area of the A2G network is the ICARO-EU. This project aims to cover the whole airspace with 4G/5G networks through the A2G links to provide efficient and reliable IFC [70]–[72]. They also utilize the Licensed Assisted Access (LAA) in addition to the 4G. Accordingly, the control and signaling information could be transferred through the licensed spectrum while sending the user data via the unlicensed spectrum. The efficiency of 4G LTE and 5G standards are compared under this project. The large bandwidth and antenna arrays of 5G with the beamforming capability increase the A2G capacity with reduced interference [73]. The large antenna arrays can ease the path losses in low wavelengths of mmWave. More specifically, 2.5 dB Signal to Interference plus Noise Ratio (SINR) is guaranteed for 4G, while it is observed as 17.5 dB for 5G technology. Similar to the ICARO-EU, the Next Generation Mobile Network (NGMN) Alliance supports using 5G technology to enable IFC through A2G networks. The NGMN achieves the user-experienced data rate of 15 Mbps per user for downlink and 7.5 Mbps per user for uplink with 10 ms end-to-end latency as shown in Table 4.

TABLE 4. A2G connectivity requirements based on 5G technology [74].

Requirements	Values
User Experienced Data Rate	15 Mbps per user for downlink 7.5 Mbps per user for uplink
End-to-end Latency	10 ms
Connection Density	60 aircraft per 18000 km^2
Traffic Density	1.2 Gbps per plane for downlink 600 Mbps per plane for uplink

One of the most prominent A2G solutions is also proposed by GoGo, which enables 2 MHz bandwidth for uplink and 850 MHz for downlink based on the 3G Code Division Multiple Access Evolution-Data Optimized standard [75]. The land-based ground structure, fuselage-mounted aircraft antenna technology, and in-cabin Wireless Fidelity (WiFi) network are the three main characteristics of the GoGo A2G network [76]. The GoGo with these characteristics can enable capacity up to 3 Mb/s. As an improvement, the ATG-4 is proposed, which allows 9.8 Mb/s peak data speeds by utilizing four antennas that can establish a connection with multiple ground stations simultaneously. Moreover, to create a high-quality link, the connection distance between the aircraft and ground station is approximately 225 nautical miles according to work in [77]. Similarly, the maximum A2G communication distances for the airplane at the 12 km altitude could be taken 428 km, 411 km, and 402 km for the 100 m, 30 m, and 10 m ground station height values [78]. Also, the minimum antenna gain for 100 km A2G distance is defined as 35.41 dB for 40 dBm transmission power and 3.4-3.8 GHz frequency band [78]. In addition to these, the Electronic Communications Commitee (ECC) proposes two frequency bands as 5855-5875 MHz and 1900-1920 MHz for A2G communications as summarized in Table 5.

1) OVERVIEW OF AIR-TO-GROUND LINKS

Communication is a necessary condition to allow a safe and orderly flow of air traffic [82]. The management of air traffic and airspace could be enabled as a result of cooperation with the airborne and ground-based functions [83]. The A2G network is first used for operational purposes before the above-explained IFC requirement. With the communication links provided through the A2G structure, the aircraft can access and share business and flight-related data in real-time. To achieve these aims, the A2G communication is firstly executed as voice communication by using the Double Sideband and Amplitude Modulation (DSB-AM), which is deployed in the VHF band between 118 and 137 MHz [84]. The DSB-AM enables reliable communication between the aircraft and ground station. However, the limitations on message size, costly transmission, and interfacing with ground-based networks reduce its efficiency with the growing air traffic.

TABLE 5. Main ground station parameters for 5855-5875 MHz and 1900-1920 MHz frequency bands [79]–[81].

Parameters	1900-1920 MHz Frequency Band	5855-5875 MHz Frequency Band
Maximum Channel Bandwidth	20 MHz	20 MHz
Nominal Channel Centre Frequency	1910 MHz	5865 MHz
Maximum Effective Isotropic Radiated Power	50 dBm/MHz	32 dBm/MHz
Receiver Adjacent Channel Selectivity	$\geq$ 43.5 dB	$\geq$ 43.5 dB
Receiver Sensitivity	$\leq$ -87 dBm	$\leq$ -87 dBm
Interfering Signal Detection Level	$\geq$ -106 dBm	$\geq$ -106 dBm

TABLE 6. Differences of L-DACS 1 and L-DACS 2 [93], [94].

Parameters	L-DACS 1	L-DACS 2
Transmit/Receive (Tx/Rx) Distance	200 nm	200 nm
Tx Output Power	41 dBm	55.44 dBm
Tx Antenna Gain	13 dBi	8 dBi
Tx Cable Loss	2 dB	2.5 dB
Rx Noise Power	-107.03 dBm	-107.99 dBm
Interference Margin	0 dB	0 dB
Safety Margin	6 dB	6 dB
Path Loss	143.76 dB	143.62 dB
Bandwidth	498050 Hz	200000 Hz
Thermal Noise Power	-117.03 dBm	-120.99 dBm

To solve this problem, the VHF Data Link (VDL) is utilized through the VHF band for data transmission. Data communication is more bandwidth-efficient with fewer errors compared to voice communication. Therefore, the A2G links are changed with the growing technology and needs as follows:

- High Frequency (HF) and Very High Frequency (VHF) Links: The HF and VHF links could be used for the aeronautical voice communications based on the Single Side-Band Amplitude Modulation (SSB-AM) and DSB-AM technologies. The HF links operate between the 3 to 30 MHz bands. These HF links could be utilized for long-range communications, and accordingly, the signals could be reflected by the ionosphere. Unlike, the VHF links work between the 30-300 MHz transmission range. The frequency ranges 108-118 MHz and 118-137 MHz are used for radio navigation and communication. Also, the ionosphere and other obstacles do not reflect its signal.
- VHF Data Link (VDL) and VHF Data Link Mode 2 (VDL-2): The inefficiency of the voice communications and saturation of VHF link constitute the main reasons for the generation of VDL [85]. The VDL refers to digital communications on the VHF band. To increase the speed of VDL data communication, the VDL-2 is proposed by utilizing Carrier Sense Multiple Access (CSMA) with 31.5 kbit/s link capacity [86]. The four VHF channels are reserved for data communications as 136.90, 136.925, 136.950, and 136.975 MHz [87]. Also, due to the LOS characteristics of these channels, the handover procedure should be executed between the ground base stations. However, the VHF saturation, lack of available spectrum, and limitations of analog radio lead to a suggestion of new data link technology called L-band Digital Aeronautical Communication System (L-DACS) [88].
- L-DACS: To satisfy the demands of the future aeronautical traffic growth, the L-DACS enables high performance with more efficient bandwidth utilization compared to the terrestrial aeronautical data links [89]. The L-DACS offers a 200-275 kbps capacity by operating L-band (960-1164 MHz). Additionally, the EUROCONTROL and FAA developed two radio access technologies based on L-DACS as follows:
  - L-DACS 1: L-DACS 1 enables the transmission of both voice and data with the 270 kbit/s on the return link and 310 kbit/s on the forward link based on the Orthogonal Frequency Division Multiplexing-Frequency Division Duplex (OFDM-FDD). More specifically, the Orthogonal Frequency Division Multiple Access (OFDMA) and TDMA are used by the RL. On the other hand, the Orthogonal Frequency Division Multiplexing (OFDM) is utilized by the FL [90]. The information of the ground station and the mobile terminal is transmitted through the FL and RL, respectively [91]. Also, the acknowledged and unacknowledged data transfer modes could be supported by L-DACS 1.
  - L-DACS 2: The L-DACS 2 is designed based on the Time Division Duplex (TDD) configuration and the Global System for Mobile Communications (GSM) with the 70-115 kb/s data rate. Here, the Gaussian Minimum Shift Keying (GMSK) is used as a modulation technique.

  The main differences between L-DACS 1 and L-DACS 2 are summarized in Table 6. As shown in this table, the performance of the L-DACS 2 is less than the L-DACS 1. Moreover, one of the critical radio navigation systems which use the L-DACS is the Distance Measuring Equipment (DME), which is used for measuring the slat distance between the ground station and aircraft by working in the 960-1215 MHz frequency band [92].
- High Frequency Data Link (HFDL): The HFDL is designed for data transmission via HF bands. The link capacity of HFDL is up to 1.8 kbit/s, and this capacity is shared between all aircrafts within the coverage area of a base station [86]. A base station can cover an area with a range of between 2500 km and 4000 km due to the unique propagation of the HF radio.

TABLE 7. Matching characteristics of WiMAX and AeroMACS [98], [99].

Characteristics	WiMAX Support	AeroMACS Requirement
Mobility	up to 120 km per hr seamless handovers IP-based architecture	High
Coverage	LOS	High
Link Breakage Resistance	NLOS Multipath	High
Resource Efficiency	OFDM	High
Security	Authentication Authorization Encryption	High
Data Rate	Adaptive Modulation Coding	High
Scalability	Binary Phase Shift Keying Quadrature Phase Shift Keying Quadrature Amplitude Modulation	High
Cost Efficiency	TDD FDD	High

- Aircraft Communications and Reporting System (ACARS): The ACARS is proposed to enable message exchange between the aircraft and ground system for the safe, secure, and efficient flight of aircraft [95]. The ACARS could offer the VHF, VDL, VDL-2, HFDL, and satellite communications to enable the message exchange. The ACARS messages could be one of the three main types of Air Traffic Control (ATC), Aeronautical Operational Control (AOC) or Airline Administrative Control (AAC). The details of these messages could be summarized as follows:
  - Air Traffic Control (ATC): These control messages are exchanged between the aircraft and Air Traffic Controllers, which are on the ground to enable safe, controlled, and efficient flight. This communication can also be called Air Traffic Services (ATSC), which is safety-critical.
  - Aeronautical Operational Control (AOC): The AOC messages are transferred between the aircraft and airlines to exchange the safety-critical messages related to the aircraft's takeoff, en-route, and landing procedures.
  - Airline Administrative Control (AAC): The airlines and aircraft exchange the aeronautical administrative messages. These messages are more related to business operations and not safety-critical. Accordingly, aircraft's safe and controlled flight does not depend on the AAC messages.
- Aeronautical Mobile Airport Communication System (AeroMACS): The AeroMACS is developed based on the IEEE 802.16-2009 Mobile Worldwide Interoperability for Microwave Access (WiMAX) standard. The AeroMACS supports 5 MHz channels in the 5091-5150 MHz band based on the OFMDA. The main aim of the AeroMACS is to enable data communication for the airport, and the requirements of this data communication firmly match with the WiMAX characteristics [96]. We summarize these matching characteristics in Table 7 based on the AeroMACS requirements and WiMAX features to support them. Thanks to these features, AeroMACS enables ground-to-aircraft connectivity by supporting ATC and AOC communications with high capacity, performance, bandwidth, per-bit cost-efficiency speed, and security [97].
- Controller Pilot Data Link Communications (CPDLC): The CPDLC enables two-way data exchange system between the aircraft and air traffic controller to allow ATC service. The VDL-2 could be used for CPDLC. The Data Link Initiation Capability (DLIC), ATC Communications Management Servic (ACM), ATC Clearances Service (ACL), and ATC Microphone Check Service (AMCS) are the primary mandatory data link services enabled through CPDLC [100]. However, the CPDLC does not use for time-critical communications.
- Aeronautical Telecommunication Network over Internet Protocol Suites (ATN/IPS)): The Aeronautical Telecommunication Network (ATN) is established by the ICAO based on the Internet Protocol Version 6 (IPv6) to enable ground-to-ground and air-to-ground communications. More specifically, one of the main aims of the ICAO is to standardize the IPv6-based ATN [101]. The ATC, AOC, AAC functionalities are also supported by the ATN system based on the CPDLC with VDL-2 [102], [103].
- Automatic Dependent Surveillance-Broadcast (ADS-B): The ADS-B is a transmission system consisting of an antenna, server, display, and ground systems with two primary functions: ADS-B Out and ADS-B In [104]. The position and velocity data are sent through the ADS-B Out functions from the aircraft. Therefore, the ATC could follow the plane in real-time more safely and efficiently. Similarly, the aircraft-to-aircraft position and velocity data are reported to the cockpit display through the ADS-B In functionality [105]. Thus, each aircraft can obtain information from other aircraft continuously. These ADS messages consist of the following information fields: Four-dimension position, flight identification, predicted route, earth reference-track, ground speed and vertical rate, air reference heading, wind speed/direction, and temperature. Additionally, the ADS-B includes the VHF elements. The VHF is used to enable air-to-air and air-to-ground communications for surveillance purposes [106]. Moreover, the Traffic Collision Avoidance System (TCAS) could be considered another type of surveillance system. But, the TCAS enables communication between aircraft, which includes an appropriate transponder. Accordingly, the plane query position information to other aircrafts through TCAS without a need for ground station [107].

The above-explained A2G links could be combined as a multilink system as shown in Fig. 4. In addition to them, the channels could be categorized according to the usage and multiple access schemes. In this grouping, the *Command Channels* are the one-way channels, and they are used for transferring the ground-to-air command messages as weather information, emergency, and reservation channel IDs. *TDMA Channels* are also one-way channels, but they are used as an air-to-ground channel to transmit the traffic control and automatic dependent surveillance messages. *ATC Voice Channels*

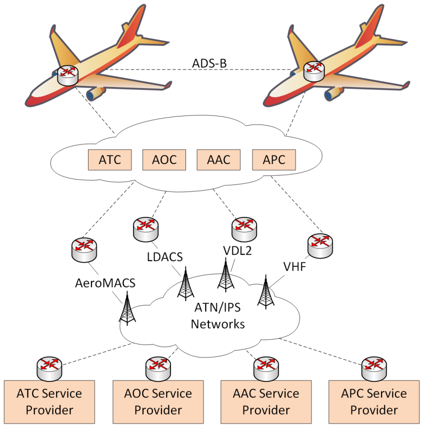


FIGURE 4. A2G Multilink system [108].

are utilized for voice communications between the air traffic controller and aircraft. During any dangerous situation, the data and voice communications are executed with duplex Emergency Channels. The *Demand Assigned Multiple Access (DAMA)* could be used for the one- or two-way voice and data communications to transfer the random and infrequent long messages. The *Reservation Channels* are the one-way air-to-ground channels that are used for providing access to the DAMA channels.

These technologies increase the efficiency of the A2G network compared to the satellites. In more detail, we show the main differences between the A2G network and satellite communication in Table 8. According to this table, the A2G network is mainly proposed to solve satellites' latency and installation/equipment cost problems with high throughput. However, the ground stations should be deployed on the terrestrial areas to enable the A2G network. This situation leads to coverage problems for aircrafts that execute remote flights over the ocean.

TABLE 8. Comparison of satellites and A2G network.

Parameter	A2G Network	Satellite
Latency	Low	High
Coverage	Low	High
Cost/Equipment cost	Low	High
Installation Time	Short	Long
Transmission Path	Short	Long
Throughput	High	Limited
Available Spectrum	Limited	High

The AANET is a promising solution for solving the satellites' latency and installation/equipment cost problems and coverage of the A2G networks. AANETs can gather both the satellite and A2G connectivity strengths under one structure, as explained in the following section.

III. AERONAUTICAL AD-HOC NETWORKS (AANETs)

The AANETs are created by establishing air-to-air links between the aircraft in the sky without relying on a central node or entity [109]. The packets of a source aircraft are routed through these links until reaching the destination aircraft having Internet connectivity. Accordingly, air-to-air links are the crucial components for the AANETs. Generally, these links have LOS characteristics by utilizing U/VHF band with 119-137 MHz spectrum, relatively high Signal to Noise Ratio, and unrestricted battery power [110], [111]. Generally, the establishment of air-to-air links is executed based on the communication range between aircrafts [112]. If the distance between two aircrafts is smaller than the transmission range, then the air-to-air link is established among these planes based on omnidirectional transmission [113]. During the packet routing through these air-to-air links, each aircraft becomes a router in AANET. Also, the destination aircraft has an Internet connection via satellite or A2G connectivity. Accordingly, the advantages of both satellite connectivity and the A2G network are combined under the AANET structure. Therefore, the coverage problem of the A2G network is solved by the AANETs as they extend the coverage area of an A2G network by enabling Internet access to the aircraft, which cannot directly access the A2G infrastructure.

As shown in Fig. 5, the AANETs have a three-layered topology [114]. In this layered topology, the top, middle, and bottom layers correspond to the satellite, aircraft, and ground layers, respectively. Each layer could interact with others using inter-layer links [115]. The satellite layer connects to the aircraft and ground layers through the satellite-to-air and satellite-to-ground links as explained in Section II-A1. Similarly, as given in Section II-B1 the air-to-ground links are used to connect the aircraft to the A2G base stations. Also, the air-to-air links are established between the airplanes to create an AANET in the aircraft layer, as explained paragraph above.

The AANETs have an ultra-dynamic and unstructured ad-hoc topology with easily broken air-to-air links. The topological characteristics of AANETs lead to some research challenges, and we investigate these challenges from a layered aspect in Section IV. At first, we will investigate the effects of environment and mobility on AANET in the following subsection since these are the main reasons for AANET topology characteristics.

A. EFFECTS OF ENVIRONMENT AND MOBILITY ON AANET

As explained above, the propagation in AANET has the LOS characteristic, and it could be modeled as free space loss. But, the propagation effects should be included in the design of these LOS systems. Here, we investigate the attenuations due to atmospheric gases and hydrometeors. We consider that the oxygen absorption, rain, and cloud attenuations could be added to the free space path loss model of AANETs. The oxygen absorption should be regarded due to the significant propagation distance of aeronautical networks. The oxygen absorption loss model and the frequency-dependent oxygen loss values for the A2G networks are summarized in Table 9 [116]. We claim that these values could also be utilized for AANETs due to the free space loss model.

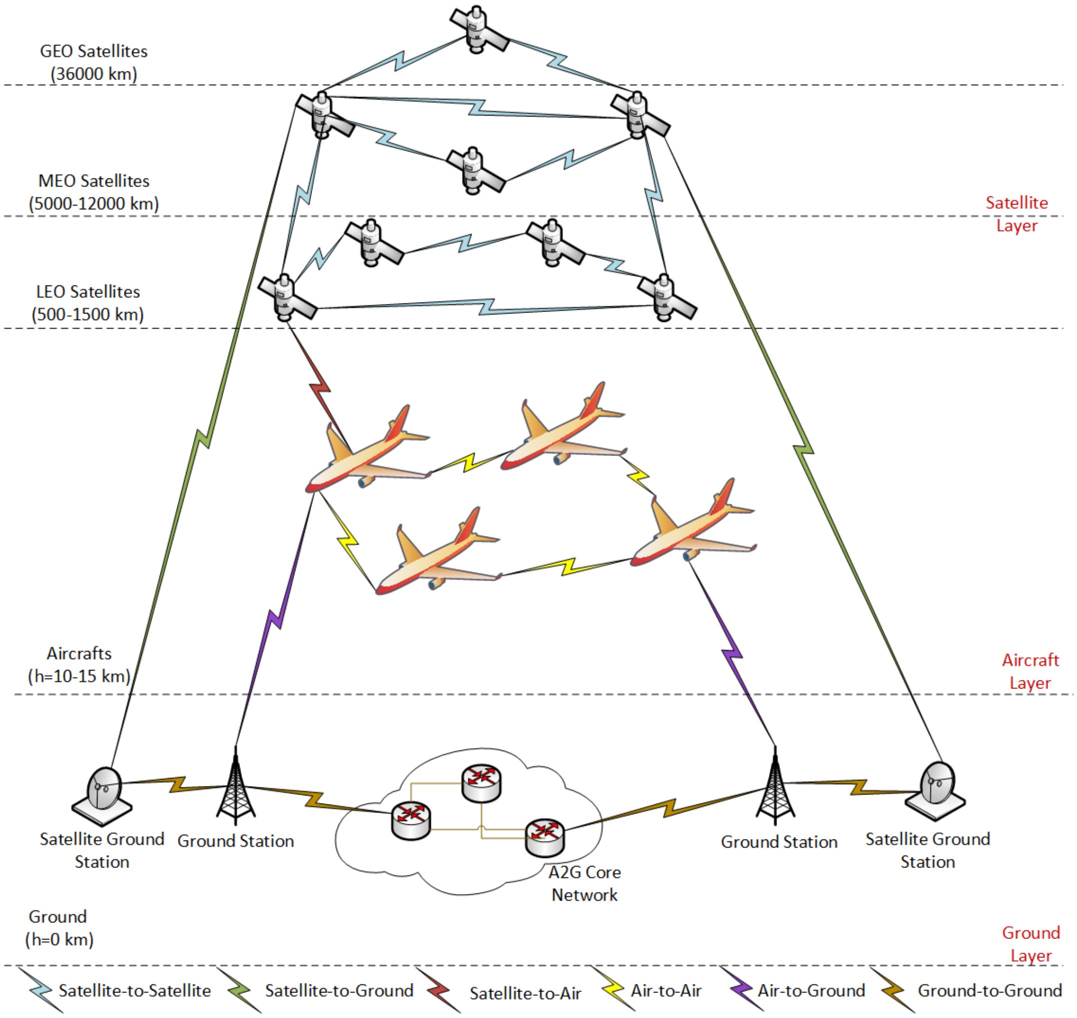


FIGURE 5. The AANET topology.

TABLE 9. Frequency dependent oxygen loss [116].

Frequency f(GHz)	0-52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68-100
α(f)[dB/km]	0	1	2.2	4	6.6	9.7	12.6	14.6	15	14.6	14.3	10.5	6.8	3.9	1.9	1	0

The rainfall and atmospheric gaseous cause absorption and scattering for frequencies above 5 GHz. This situation increases the transmission losses by leading to high channel error rates [117], [118]. Additionally, the loss of signal strength and transmission power could be listed as the main attenuated factor caused by the rain. More specifically, in AANET, the air-to-air links between the aircraft could be easily broken due to the rain attenuation effect. This situation causes quick topology change, as observed in the mobility effect case. Therefore, the rain attenuation should be included in the propagation model for the frequencies above 5 GHz, as shown in Table 10. Also, the rain attenuation could be defined as $A_r = kR^{\alpha}$ (dB/km) [119]. Here, k and α are the functions of frequency and polarization, while R defines the rain rate. The water or ice particles in clouds also cause attenuation of transmitted signals through the air-to-air links between the aircraft. This effect becomes more important for the higher frequencies, as shown in Table 10. The cloud attenuation could be calculated as $A_c = KM$ (dB/km) [120]. In this equation, the K and M represent the cloud's attenuation coefficient and liquid water density. One possible solution to reduce this effect is the optical link utilization during the en-route phase since clouds drop their performance in lower altitudes. The cloud and rain attenuations for different frequencies are shown in Table 10.

As shown in Fig. 6, the flight pattern of aircraft is modeled in seven phases taxiing, takeoff, climb, cruise/en-route, descent, approach, and landing. During these phases, the aircrafts fly at different altitudes, and these altitudes affect the aircraft modeling. More generally, the aircraft fly in the lower

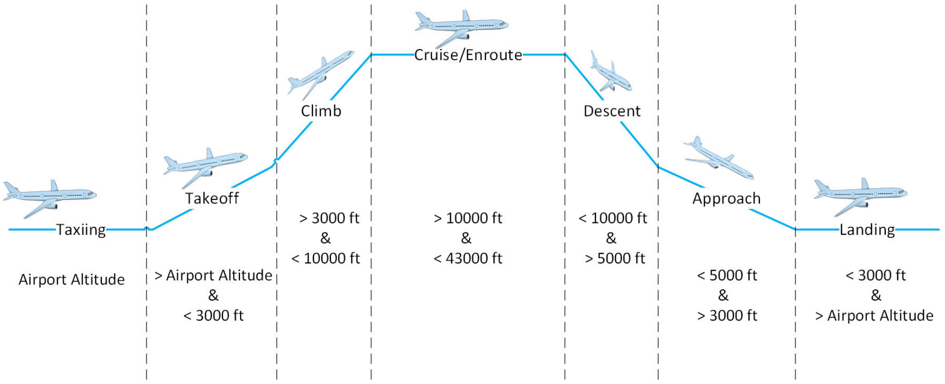


FIGURE 6. The pattern of flight [124].

TABLE 10. Attenuation by cloud and rain [121].

Frequency f(GHz)	Cloud Attenuation [dB]	Rain Attenuation [dB]
5	0.023	0.0313
10.7	0.106	0.249
15.4	0.217	0.528
23.8	0.507	1.114
31.4	0.859	1.574
90	4.74	3.17

altitudes of the stratosphere. Accordingly, the propagation in an AANET has LOS characteristics. It could be modeled as free space loss or linear uniform motion during cruise/en-route since buildings or objects could not block the links. In addition to these general models, the Poisson process and Improved Semi-Markov Smooth Mobility Model could be used for aircraft modeling [122], [123]. Here, the Poisson process is generally used during the takeoff and approach phases since we have an exact random timing for events with the known average time between events. Also, the Improved Semi-Markov Smooth Mobility Model aims to simulate aircraft mobility based on the physical law of airplane motion. For this reason, it could be used during the seven phases of aircraft mobility.

The mobility characteristics of aircraft could be considered pseudo linear in AANET. This means that the aircraft can move with a relatively linear path without changing direction and motion parameters. Therefore, the nodes in AANET generally have a regular and predictable movement. However, the ultra-high speeds of aircraft limit this predictable movement, and time-varying link characteristics lead to rapidly changing network topology. Accordingly, the links between the aircraft could be quickly established and broken. Moreover, the frequent reorganization of the network also complicates the regular monitoring of the network [125]. For these reasons, ultra-high-speed and 3D movement characteristics should be considered to establish more durable air-to-air links between the aircraft. The sustainability of the AANET topology is increased with these durable air-to-air links. Accordingly, the AANETs can observe fewer packet losses and drops with higher transmission success.

As explained in this part, the effects of environment and mobility cause different research challenges for AANETs. In the sequel part, we will investigate these research challenges by evaluating the state-of-the-art from a layered aspect.

IV. OPEN RESEARCH CHALLENGES FOR AERONAUTICAL AD-HOC NETWORKS

The effects of environment and mobility lead to research challenges in the Data Link, Network, and Transport layers. In this section, we explore these challenges by investigating the solutions in the state-of-the-art.

A. DATA LINK LAYER ISSUES

We investigate the data link layer issues in three parts as Link Stability, Link Connectivity, and Medium Access Control (MAC) requirements in AANET as shown in Fig. 7. Here, the Link Stability and Connectivity Requirements are related to the Logical Link Control (LLC) of layer two as explained follows:

1) LINK STABILITY REQUIREMENT IN AANET

The AANETs have a highly dynamic topology caused by ultra-high speeds of aircraft. This situation makes the AANET environment challenging for the data link layer since it is hard to manage the air-to-air and air-to-ground links in these dynamic conditions. Additionally, the atmospheric effects can reduce the quality of these links through oxygen absorption, rain, and cloud attenuation. Therefore, one of the main aims in the data link layer is to enable link stability under these conditions. Here, the main effects on link stability in AANET could be listed as follows: *direction, expiration time, and Doppler effect*.

- *Direction Effect on Link Stability:* The links could be established between the aircraft flying in the same direction to enable link stability. The main reason for this consideration is that the links between the aircraft moving to the opposite directions are unreliable due to the

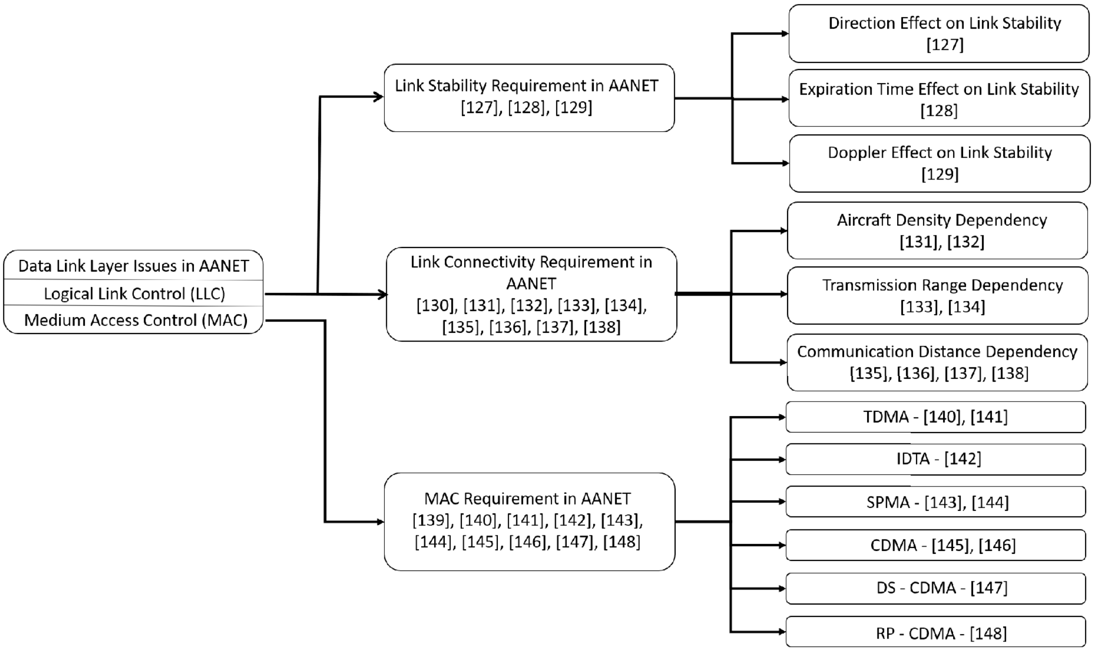


FIGURE 7. Data link layer issues in AANET.

Doppler shift effect. More clearly, the links between the aircraft in the same direction are likely to last longer than in opposite directions. Another possible solution is a two-phase transmission scheduling scheme. In the first phase, the horizontal transmission is executed between the aircraft at the same height until the packets reach the nearest plane to the destination. Then, the relay aircraft realizes the vertical transmission to the destination. In this way, the links are more efficiently utilized for packet transmission. Similarly, the available link probability could be detected to control the topology [126].

- *Expiration Time Effect on Link Stability:* The link and path expiration times are estimated based on the relative velocity and position of aircraft to increase the AANET link stability in [127]. Here, the relative velocities could be found using the Global Positioning System (GPS) and power or Doppler shift. Here, the relative movement of the transmitter and receiver leads to an apparent change in the frequency of transmitted electromagnetic signals, and this effect is called a Doppler shift. The Doppler shift as a link stability metric is more efficient since the atmosphere and rain can attenuate the radio signals in GPS and power methods.
- *Doppler Effect on Link Stability:* The Doppler shift could be calculated by comparing the expected and received radio signal frequencies between the aircraft and satellites, and the Doppler shift of control packets could be utilized to calculate the link duration [128]. The aircraft can remain within the LOS of other aircraft if the positive Doppler values are calculated. Also, the stability of the link is increased with the smaller Doppler value. These situations will provide a more persistent connection between the aircraft by also reducing the total handover number.

Based on these main effects on link stability, we consider that the direction, expiration time, and Doppler Effect should be regarded during the formation of AANETs. More clearly, we should establish the air-to-air links between aircraft with similar flight characteristics on the same movement route to disable the direction effect with higher expiration time and more negligible Doppler Effect.

2) LINK CONNECTIVITY REQUIREMENT IN AANET

The effects of the environment and mobility reduce the link connectivity in AANET. The reduced connectivity leads to packet losses by increasing breakage rates. On the other hand, we can reduce the packet losses by establishing more durable links between aircrafts. At this point, the link connectivity depends on the *aircraft density* on flight path, *transmission range*, and *distance* between two aircrafts detailed as follows [129]:

- *Aircraft Density Dependency:* The communication range for network connectivity decreases with increasing aircraft density, according to work in [130]. The Bernoulli experiment could be used to find the relationship between the node density and the probability of forming a network in AANETs. According to the Bernoulli and Poisson estimations, the likelihood of creating an AANET increases with the growing aircraft density. Also, the connectivity of AANET is restored by the movement of the relay nodes in [131]. They utilize an online optimization approach to control the activities of the relay nodes.

- *Transmission Range Dependency:* The necessary and sufficient transmission range to show the connectivity requirement in AANET is defined in [132]. The necessary transmission range is used to indicate the conditions based on the disconnection probability of AANET. In contrast, the sufficient transmission range represents the conditions to obtain a connected AANET with one possibility. The necessary and sufficient transmission ranges are defined as a function of the aircraft density, flight path length, and airspace separation. Here, the airspace separation divides the airspace into multiple height levels to define 2-dimensional AANETs. Additionally, the hop count between the nodes could affect the transmission range. If the communications are executed based on the single hop model, then the source node can directly communicate with the destination [133]. However, in a two-hop model, the source to destination communication is done through relay nodes with higher throughput.
- *Communication Distance Dependency:* Communication distance plays a vital role in link connectivity. Generally, this distance is determined according to the Earth's curvature and the aircraft's flight level. The aircraft at low flight levels experience higher connectivity by creating longer communication distances [134]. If we want to determine the stable number for communication distance, the air-to-air communication range could be taken as the 450 nautical miles at 35000ft [135]. Also, the maximum distance between the aircraft is defined as 444 nautical miles at 32808ft [136], [137].

The AANETs could be more easily created in areas with higher aircraft density. The air-to-air link distances decrease with the increasing number of aircrafts in these areas. This means that the dependency on the transmission range is satisfied by most aircrafts, and accordingly, more long-lasting connections are established between them.

3) MEDIUM ACCESS CONTROL (MAC) REQUIREMENT IN AANET

The MAC protocols in the terrestrial links could not be effectively utilized to satisfy the requirements of AANETs. However, the management and allocation of these links are crucial factors to control the network performance for aeronautical networks [138]. One of the common considerations is to utilize the CSMA techniques in the AANET, but the high traffic load on the network increases the collision probability and delay. More specifically, the high number of waited packets in the aircraft queues grows delay and losses. For this reason, the single TDMA channel is aimed to use with AANET instead of CSMA in [139], [140]. The Interference-based Distributed TDMA Algorithm (IDTA) is also proposed for AANET to diminish the problems of basic TDMA [141]. It can run both the sender and receiver of a link to reduce the computational load of the receiver node, but it observes the delay problems. As a solution to delay related problems, the Statistical Priority Multiple Access (SPMA) protocol is proposed in [142], [143]. This priority access technique works based on the statistics of channel occupancy, and here, the congestion degree of the channel is compared with the channel accessing threshold of packets. This method reduces the waiting time observed for taking the channel control compared to the CSMA. Also, during a conflict, the nodes wait a random amount of time before re-transmission. Additionally, to solve the capacity-related problems, the Code Division Multiple Access (CDMA) could be utilized because of the higher capacity advantage [144]. This work also considers that the TDMA and also Frequency Division Multiple Access (FDMA) is inefficient due to the high load caused by high aircraft numbers. Clearly, the FDMA and TDMA are not efficient for the AANET due to bandwidth reduction and clock synchronization problems. Similar to this work, the CDMA is used to enable simultaneous communication opportunity to the aircraft [145]. As an extension to the CDMA, the Direct Sequence CDMA (DS-CDMA) is proposed as an allocation method in work [146]. The main reason for selecting the DS-CDMA is that it can allow multiple simultaneous transmissions without coordination among nodes. Similarly, the Random Packet Code Division Multiple Access (RP-CDMA) could be utilized by assigning randomly selected spreading codes to each transmission [147].

We can state that the AANETs do not utilize the terrestrial-based MAC protocols due to the ultra-dynamic and unstructured characteristics. Accordingly, we should design a new MAC protocol for AANET by considering its specific features. Generally, the designed protocol should work in an ad-hoc manner without a central entity or coordination according to AANET topology. Additionally, the design phase of the MAC protocol should include the high packet load on the network and collision probability between aircraft.

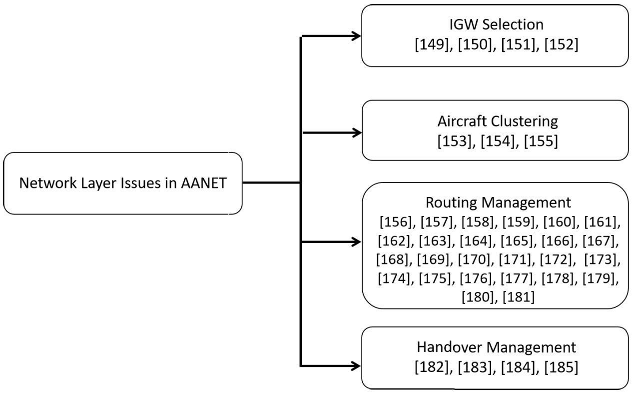


FIGURE 8. **Network layer issues in AANET.**

B. NETWORK LAYER ISSUES

In this survey, we investigate the network layer issues in four parts IGW selection, aircraft clustering, routing management, and handover management, as shown in Fig. 8. The details of these issues could be explained in the following subsections:

FIGURE 9. A possible AANET clustering [148].

1) Internet Gateway (IGW) SELECTION

The IGWs are deployed to connect the AANET to the Internet. Therefore, all packets are transferred through the IGWs during the operation of AANET, and the congestion probability is higher than other nodes. For these reasons, the IGW selection is essential for the success of the AANETs. This selection generally could be executed proactively or reactively. In the proactive gateway discovery, the gateways periodically send advertisement messages to announce their presence to a network. The node transfers gateway solicitation messages to the network for taking gateway advertisements in the reactive gateway discovery approach. Also, the IGW selection based on the distance in terms of hop count constitutes one of the possible methodology [149]. Here, the packet delays potentially increase with the distance between the mobile node and a gateway. The IGW selection based on the defined utilization metric is proposed as another possible method [150]. Here, the traffic carried by a gateway is divided by the wireless interface capacity as a utilization metric. Accordingly, the traffic loads are shared between the IGWs by also maximizing connectivity [151].

Additionally, the delay-based IGW selection scheme could be utilized to increase the packet delivery ratio and fairness by decreasing the average packet delay. This delay is affected by the traffic on a path and gateway. This delay could be estimated by putting a time stamp on the gateway advertisement messages. Also, the variance between the delays of these successive gateway advertisements could be used as an IGW selection parameter [152].

The IGWs are the most loaded nodes on the AANET topology since it is an Internet connection point of the whole topology. For this reason, the load and connection density metrics should be considered during the IGW selection. Additionally, it should be reasonably close to the Internet access point due to the same reason. At that point, the shortest path or topological spanning algorithms can help determine the IGW according to its location. Here, the load and location-based methodologies could also be combined as a hybrid selection methodology.

2) AIRCRAFT CLUSTERING

The main aim of the clustering is to collect the aircraft having similar direction, velocity, angle, and mobility attributes in a common set. Accordingly, we can obtain a stationary AANET topology with long-lasting air-to-air links. More specifically, the links between the aircraft having more similar attributes could be maintained for a long time and this situation increases the AANET topology's sustainability. Therefore, a multi-dimensional clustering model could be utilized for aircraft clustering by taking the position, velocity, or mobility as separate dimensions as shown in Fig. 9. Two different clustering algorithms as Dynamic Doppler Velocity Clustering (DDVC) and Dynamic Link Duration Clustering (DLDC) are proposed in [153]. IN DDVC, the main clustering metric is the relative velocity between the nodes obtained through the Doppler value of packets. Accordingly, the DDVC is utilized if the position or velocity information could not be obtained directly. On the other hand, the DLDC utilizes the link expiration time estimated by using the position and velocity parameters. Similarly, the 1-hop clustering algorithm is proposed based on three steps in work [154]. Here, the first step is the neighbor discovery with periodic hello messages that include current position and speed information. Then, the cluster head is determined by taking advantage of neighbor numbers and relative speed parameters. Finally, the stability structure clustering algorithm is used for merging the clusters if the two cluster heads move to the communication range of each other. Additionally, the honeycomb division-based clustering algorithm is proposed in [155]. In this algorithm, the whole area is divided into hexagonal regions, and a cluster consists of a different number of hexagons. Accordingly, the cluster head is selected from these hexagons and the spanning tree algorithms are used to prevent the overlaps between the hexagons. Also, the Doppler velocity clustering could be used, and in this clustering method, the backbone aircraft is selected as a cluster head. Here, the cluster head sends a beacon to the neighbors and checks the Doppler shift of the beacon replies to determine the aircraft to be connected. The aircraft can also become a member of different clusters at the same time, and it can enable communication between these clusters.

Moreover, we claim that the clustering could be executed based on the spatio-temporal characteristics of aircraft. Here, the aircraft's spatial position is considered together with its changing parameters over time. According to the defined clustering algorithm, these parameters could be speed, height, or angle. Additionally, the air-to-air link establishments between the aircrafts under the same cluster should also be determined with the clustering algorithm.

3) ROUTING MANAGEMENT

In addition to the above issues, the specific characteristics of AANETs should be considered during the design of the routing algorithms. For this aim, the *Multipath Doppler Routing (MUDOR)* is proposed, which considers the mobility and link duration as routing parameters [156]. The main aim of the MUDOR is to find a more stable path to transfer the data to the destination. Here, the Doppler value is used for estimating the quality and stability of routes as shown in Table 11. Also, thanks to the multipath characteristics, the remote cluster or aircraft could participate in the routing procedure. In the *Geographic Load Share Routing (GLSR)* algorithm, the packets are forwarded to the geographically closest neighbor of the destination. Here, greedy forwarding is utilized to choose the best neighbor, which maximizes the advance of a packet. During this routing, queuing delay and link congestion probability are also aimed to reduce by enabling load sharing among the neighbors. The main reason for this is that the transferring packets can wait in the relaying aircraft queues, which possibly increases the end-to-end delay of the packet transfer in AANET [157]. To reduce this queuing delay of a packet, the GLSR takes advantage of the Join the Shortest Queue approach [158].

The *Hierarchical Space Routing Protocol (HSRP)* is proposed as an improvement of the Zone Routing Protocol which cannot be applied to the AANETs [159], [160]. The HSRP uses the flight flow rate, flight speed, and air vehicle density parameters to change the frequency of the HELLO beacons during the routing. The exchange of these HELLO messages is essential for detecting and maintaining links between two aircraft in the topology-based routing protocols. The *Path Link Availability Routing Protocol (PLAR)* uses the link stability for network topology control [161]. Also, multi-point relaying is the leading technology used in PLAR to reduce redundant transmission messages during the broadcast. The multi-point relay set includes the multi-point relay nodes. This routing protocol uses two different algorithms as the production way of the multi-point relay set. These algorithms are chosen according to aircraft density in the investigated area. The *Ad-hoc Routing Protocol for Aeronautical Mobile Ad-Hoc Networks (ARPAM)* is proposed based on the Ad hoc On-Demand Distance Vector (AODV) and Topology Dissemination Based on Reverse-Path Forwarding [162]. The main aim of ARPAM is to discover the shortest route by using different parameters like distance and the number of hops between nodes. In ARPAM, if an aircraft wants to communicate with another node, it sends a Route Request (RREQ) message through the omnidirectional link. The destination aircraft sends a Route reply (RREP) message back to the source node to show the existence of a valid path.

The *AeroRP* takes the routing decisions per-hop basis without any knowledge about the end-to-end source to the destination route [163]. In AeroRP, the velocity-based heuristics are calculated for each one-hop neighbor. Also, the time to intercept is the primary metric used during the routing decisions. With this parameter, the source node can have information about the duration when the potential neighbors are in the transmission range of the destination. Accordingly, this parameter is calculated by the source node for each neighbor. Also, the speed and coordinates are the main components for the time to intercept calculation. Additionally, the *Secure AeroRP (SAeroRP)* is proposed to increase the security of AeroRP by disabling active and passive attacks with the X.509 authentication [164].

The *Anticipatory Routing* uses the past movement history of the endpoint to predict future locations [165]. More specifically, linear regression is utilized to predict endpoints' future locations and departure times. By estimating the trajectory, direction, and affiliation/departure, the location of endpoints is reached. Then, the traffic is routed to this new location before the movement. They claim that this situation improves routing performance compared to the reactive methods. The *Spray Routing* executes traffic multicasting in the vicinity of the last known location of the endpoint [166]. Here, the sprayed packet first unicast to a node close to the destination, then this packet is multicast to the multiple nodes around the destination. During this process, the width and depth become the main routing parameters. The width represents the neighbor level number to which the packets should be multicast. The depth indicates the hop distance of the point where multicast starts to destination. In *Greedy Forwarding* algorithm, each sender aircraft marks the packet with the destination location. Then, each forwarding node decides locally to the next hop according to the relative location of the neighbor to the corresponding destination. For this reason, each aircraft should know its position and neighbors' positions. Therefore, the exchange of position information is executed only between the neighbors locally with the reduced overhead [167]. But here, the nodes should have a sufficient number of neighbors to apply the greedy forwarding mechanism [168].

The *Reactive Greedy Reactive (RGR)* protocol is proposed to combine reactive routing, and greedy geographic forwarding [169]. In this protocol, the source node transmits the route request packets to the network for route discovery, similar to the AODV approach. After receiving a route response from the destination node, the route is established. But, the transmission of the route request and response packets causes overhead on the network. This overhead of the RGR protocol is aimed to reduce in two steps as RGR with scoped flooding and RGR with delayed route request [170]. Similarly,

TABLE 11. Routing protocols for AANETs.

Protocol Name	Ref.	Parameters	Path Selection Criteria
Multipath Doppler Routing (MUDOR)	[156]	Mobility Link Duration	Doppler Value Stability
Geographic Load Share Routing (GLSR)	[157], [158]	Queue size Geographic Distance	Load Sharing
Hierarchical Space Routing Protocol (HSRP)	[159], [160]	Flight Flow Rate Flight Speed Air Vehicle Density	HELLO Beacon Update Frequency
Path Link Availability Routing Protocol (PLAR)	[161]	Link Stability Aircraft Density	Multi-Point Relaying
Ad-hoc Routing Protocol for Aeronautical Mobile Ad-Hoc Networks (ARPAM)	[162]	Position Coordinates Velocity Vectors Distance	RREQ Messages
AeroRP	[163]	Time to Intercept	Velocity-Based Heuristics
Anticipatory Routing	[165]	Endpoint of Locations	Prediction of Future Locations Linear Regression
Spray Routing	[166]	Width and Depth	Vicinity of Last Known Location
Greedy Forwarding	[167], [168]	Distance to Destination	Locally Optimal Greedy Choice
Reactive Greedy Reactive (RGR)	[169]	Location Distance	RREQ and RREP messages
Node Density Trajectory Based Routing (NoDe-TBR)	[172]	Aircraft Density	Selected Geopath
Greedy Perimeter Stateless Routing (GPSR)	[173]	Location Distance	ADS-B Messages
ADS-B Based Greedy Perimeter Stateless Routing (ADS-B/GPSR)	[174]	Security addition to GPSR	Hybrid hash function Cryptographic signature block
ADS-B Aided Geographic Routing Protocol (A-R)	[175]	Distance Relative Velocity Position	ADS-B Messages
Delay aware Multipath Doppler Routing (DMDR)	[176]	Queuing delay Relative Velocity	Doppler Value
Node Mobility and Traffic Load Aware Routing (NTAR)	[177]	Doppler Value Queue lengths	Mobility and traffic loads of nodes
Multiple QoS Parameters-based Routing Protocol (MQSPR)	[178]	Path Availability Period Available Path Load Capacity Path Latency	QoS Guarantee
QoS Multipath Doppler Routing (QoS-MUDOR)	[179]	Doppler Value QoS Parameters	FOBREQ Messages
Geographic Routing Protocol for Aircraft Ad Hoc Network (GRAA)	[180]	Topology Information Destination Position Unique Identification Number	Locally Optimal Greedy Choices
Link Longevity-Based Routing Protocol	[181]	Aircraft Positions Velocities	Link Longevity Prediction

to reduce the route discovery overhead and packet dropping probability, the Modified-RGR is proposed in [171]. In Modified-RGR, the main aim is to keep all discovered paths in a table while only the primary path is used. Therefore, the number of the route discovery process is reduced with network overhead and delay. According to the *Node Density Trajectory Based Routing (NoDe-TBR)*, the sender aircraft specifies both the packets' destination position and geographic path according to this destination position [172]. This routing algorithm consists of two main parts geopath computation and forwarding strategy. It is desired that the selected geopath is short, and the density of the aircraft on this path is high. Therefore, the actual aircraft densities are considered to maximize the packet delivery. The *Greedy Perimeter Stateless Routing (GPSR)* is proposed by taking advantage of ADS-B [173]. The main aim is to reduce the overhead and collision probability causing the geographic routing mechanism. In geographic routing, each node requires neighbors' and destination positions. Accordingly, the stages of obtaining these parameters are the main reason for the overhead in geographic routing. In the ADS-B combined GPSR, the neighbor table is created and updated with the periodic state vector broadcasts in ADS-B messages to reduce the overhead. Similarly, the *ADS-B Based Greedy Perimeter Stateless Routing (ADS-B/GPSR)* is proposed to increase the security of the GPSR with the message integrity addition to ADS-B [174]. This message integrity is provided through a hybrid hash function/cryptographic signature block.

Additionally, the *ADS-B Aided Geographic Routing (A-R)* is proposed in [175]. Here, routing operations among aircraft are executed in three parts neighbor discovery, next-hop decision, and forwarding strategy. The *Delay aware Multipath Doppler Routing (DMDR)* uses the Doppler shift, expected

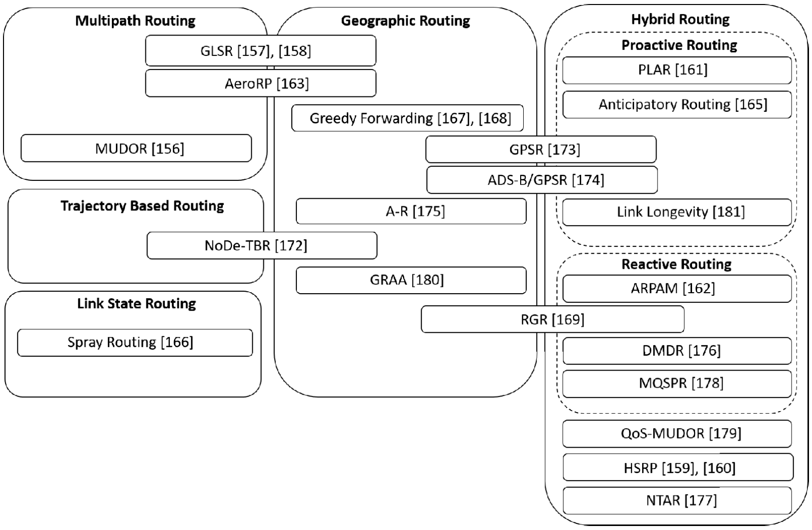


FIGURE 10. Basis of AANET routing.

queuing delay of packets, and relative velocities to select the stable and efficient paths for routing [176]. Also, with these parameters, it is achieved that load sharing among all neighbors with reduced link congestion. As a very similar method to the DMDR, the *Node Mobility and Traffic Load Aware Routing (NTAR)* considers both mobility and traffic loads of nodes at the same time [177]. This routing protocol uses the Doppler value and transmission queue length as mobility and traffic load metrics. The *Multiple QoS Parameters-based Routing (MQSPR)* utilizes the path availability period, available path load capacity, and path latency metrics for route selection [178]. With these metrics, stable paths are selected, and the traffic is balanced between these air-to-ground paths. Accordingly, they expect to observe reduced congestion, end-to-end delay, and packet loss rate during routing. Also, this work proposes to forward the best advertisement for the route discovery process. Here, they aim to prevent excessive advertisement flooding by only forwarding the best packets. The *QoS Multipath Doppler Routing (QoS-MUDOR)* uses the Doppler value and Quality of Service (QoS) parameters to select more stable paths [179] Also, during this path selection, the RREQ messages are sent in the form of Forward Best Request (FOBREQ). Here, only the best packets are forwarded, and others are discarded. The sender creates a packet by including geographic position information of destination and unique node identification number in *Geographic Routing Protocol for Aircraft Ad Hoc Network (GRAA)* [180]. Also, different from other geographic routing protocols, it can adapt the topology changes by using mobility information received from the ground station. The *Link Longevity-Based Routing Protocol* proposes a method to predict the link longevity [181]. The aircraft positions, velocities, and SINR of the received signal from neighbor aircraft are used during the link longevity prediction. The maintenance of link and route is increased with reduced topology update overhead by predicting the link longevity. The main parameters and path selection methodologies of the above-explained routing algorithms are summarized in Table 11. Additionally, all of these AANET routing algorithms are built based on different ad-hoc routing protocols, as shown in Fig. 10.

Although there are various routing algorithms in literature as detailed above, the Artificial Intelligence (AI)-based methodologies are not proposed in any work. On the other hand, we claim that the AI-based routing algorithms adapt to the dynamic conditions of AANETs by considering the instant status of each aircraft. At that point, one of the possible solutions is to utilize reinforcement learning for routing management. Here, aircraft can take their own routing decision through exploration and exploitation without any guidance.

4) HANDOVER MANAGEMENT

As explained above, the mobility and atmospheric effects cause link breakages by reducing their qualities in AANET. Here, the significant propagation distance between aircraft increases the oxygen absorption effect, and this situation reduces the air-to-air link quality between them. Also, the absorption and scattering effects grow with the rain and cloud. These effects lead to frequent air-to-air link breakages by reducing signal strength. Similarly, the highly dynamic AANET environment caused by the ultra-high velocity of aircraft increases the link breakages by leading to frequent aircraft replacements. These broken links should be established again to the other aircraft as shown in Fig. 11. This transferring is executed through the handover procedure as shown in Fig. 9.

The following works do different handover management algorithms and performance evaluations in the literature. Accordingly, a handover mechanism consisting of three phases: information collection, handover decision, and handover execution is proposed in [182]. In the information collection phase, the parameters like signal strength and bit error rate are continuously monitored and compared with the

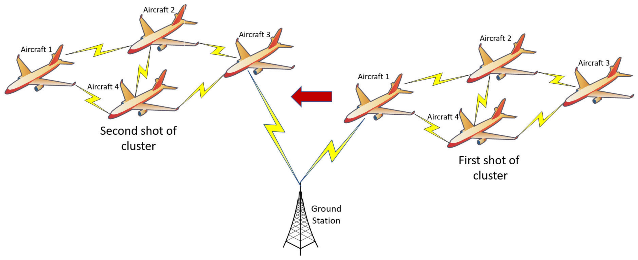


FIGURE 11. **Sample handover procedure on AANET.**

threshold values. According to the comparison results, the handover decision is taken in the second phase. Then, the handover is executed based on the Mobile IP and Resource Reservation Protocols (RSVP). With this handover mechanism, the geographic proximity and congestion parameters control the associated IGW of an aircraft. Therefore, all communications on an IGW are transferred to another gateway. Here, the congestion of an IGW is defined as the maximum transmission buffer from all links. One of the main aims of the handover procedure is to balance traffic load among IGWs according to the congestion parameter. This congestion-aware handover strategy will also increase the per-aircraft bandwidth [183]. Moreover, the handover performance in L-DACS 1 access network based on the IPv6 functionality is analyzed in [184]. Here, the ground station polls the received signal strengths of the neighboring cells through broadcast control information messages. If the received signal level of the neighbor station is greater than the current one, then the current cell triggers a handover to this cell through the HO_COM message. Then, the CELL_EXIT message is transferred to the current station, and the connection is switched to the channel of the selected station. In addition to these, the dual connectivity for the aircraft connections is proposed by utilizing VHF, and mobile user objective links [185]. Accordingly, the handover management is executed under these dual connectivity conditions. During the handover management, the queue backlog, user fairness, and resource constraints are also considered to reduce the delay.

As explained above, the aircraft clusters can change continuously due to the ultra-dynamic characteristics of AANETs. Accordingly, the AANET experiences higher handover rates due to these continuous changes. As such, one of the possible solutions is to estimate the subsequent movements of aircraft to take precautions for the upcoming handovers. By estimating the next handovers, we can pre-determine the clusters that the aircraft will connect. Then, we can assign the aircraft to these pre-determined clusters to reduce the delays during the handover.

C. TRANSPORT LAYER ISSUES

As explained above, the AANETs have specific features and requirements compared to the terrestrial networks. The current transport protocols cannot satisfy these requirements as in data link and network layers. As an example, the frequent retransmissions of lost packets in Transmission Control Protocol (TCP) reduce the AANET performance by causing a high delay. Also, the highly asymmetric channels can cause congestion on the reverse link. This congestion could be assumed to be the main reason for the packet loss, which possibly reduces the throughput in AANET. On the other hand, if the User Datagram Protocol (UDP) is used as a transport protocol, the transmissions are executed more fastly with reduced reliability. For these reasons, as shown in Fig. 12, different UDP and TCP-based solutions are proposed for AANET. Accordingly, by combining the TCP reliability and UDP low latency features, the Reliable User Datagram Protocol (RUDP) is presented in [186], [187]. But, the performance degradations caused by acknowledgments and retransmissions also affect the efficiency of RUDP. The FRUDP is proposed by combining the RUDP and the fountain code schemes in [188]. The main aim of this protocol is to obtain a reliable and efficient data transfer protocol for AANETs.

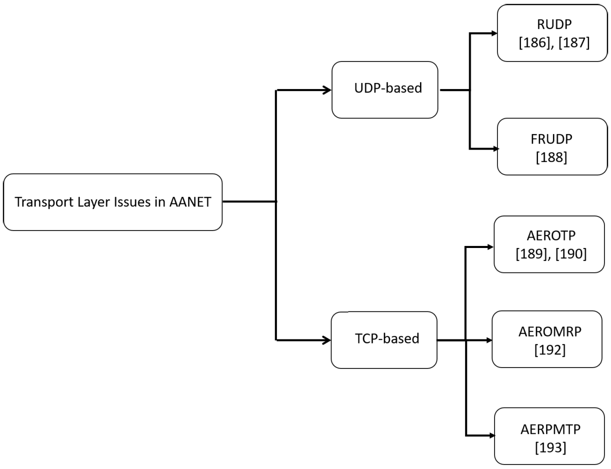


FIGURE 12. **Transport layer issues in AANET.**

Furthermore, the AeroTP is proposed as a TCP-friendly transport protocol [189], [190]. The AeroTP includes the connection setup, management, transmission control, and error control functionalities. The AeroTP also has multiple transfer modes to support reliable, near-reliable, quasi-reliable, and unreliable connections. As another approach, the Aeronautical Multipath Reliable Protocol (AeroMRP) utilizes Raptor codes as a forward error correction mechanism to avoid and mitigate the retransmission and head-of-line blocking problems [192]. The head-of-line problems reduce the transport protocol performance if the different network conditions are valid for paths. But, the AeroMRP takes advantage of path diversity by using various aeronautical networks simultaneously. Similarly, a fountain code-based multipath transport protocol (AeroMTP) effectively utilizes the available bandwidth, and path diversity [193]. The AeroMTP deploys as a TCP-friendly congestion control mechanism and uses fountain codes as forwarding error correction codes in data recovery.

TABLE 12. Summary of open research problems.

Layer	Aspect	AANET Requirement	Ref.	Recommendation
Data Link Layer	Logical Link Control (LLC)	Link Stability	[126]	Direction based link stability
			[191]	Free space loss based link stability
			[127]	Expiration time based link stability
			[127], [128]	Doppler Shift based link stability
		Link Connectivity	[130], [131]	Aircraft density dependent link connectivity
			[132], [132]	Transmission range dependent link connectivity
			[135], [136], [137]	Communication distance dependent link connectivity
	Medium Access Control (MAC)	MAC	[139], [140]	TDMA
			[144], [145]	CDMA
			[146]	DS-CDMA
			[147]	RP-CDMA
			[142], [143]	SPMA
			[141]	IDTA
Network Layer	Network Management	IGW Selection	[149]	Hop count based selection
			[150]	Utilization based selection
			[151]	Traffic load based selection
			[152]	Delay between gateway advertisements based selection
		Aircraft Clustering	[153]	Multi-dimensional clustering
			[154]	1-hop clustering
			[155]	Honeycomb division based clustering
		Routing Management	[156]- [181]	Summarized on Table 11
		Handover Management	[182], [183]	Congestion aware handover
			[184]	Signal strength based handover
			[185]	Dual connectivity based handover
Transport Layer	End-to-End Management	UDP Based	[186], [187]	RUDP
			[188]	FRUDP
		TCP Based	[189], [190]	AeroTP
			[192]	AeroMRP
			[193]	AeroMTP

As explained through this section, we investigate the open research problems of AANETs in a layered manner as data link, network, and transport layers. We summarize all of these open research problems and proposed methods in Table 12.

D. ADDITIONAL ISSUES

1) EFFECTS OF THE AIRCRAFT ANTENNAS ON CONNECTIVITY

The IFC is enabled through the aircraft antennas implemented based on the utilized aeronautical network type. Accordingly, the effects of the antenna parameters, directions, and gains should be considered while enabling the IFC. During the antenna design, one of the important metrics is the antenna gain, and it should be higher to compensate for the path loss caused by a significant distance and high carrier frequency [194]. Additionally, the antenna array should be large in aircraft compared to the lower FANETs like Unmanned Aerial Vehicles (UAV). In addition to these, the communication generally is executed based on the LOS propagation. This leads to the antennas' directions and the ranges between the aircraft having a crucial effect on the aircraft connectivity. More specifically, if an aircraft is out of the coverage range of an A2G station, it is not connected to this network. Similarly, if the distance between two aircraft is more than the predetermined distance, they cannot connect through air-to-air links. At that point, aircraft antennas' directions and parameter settings (antenna gain, azimuth beam-width, polarization) are essential in determining these A2G and air-to-air link distances. Also, the characteristics of aeronautical networks are different from the terrestrial-based conditions. Here, the dynamic characteristic of aeronautical networks makes the location of the antennas critical. Accordingly, they should be optimally located to disable the interference with the other aircraft systems [195].

2) EFFECTS OF REGULATIONS

This part of our article summarizes more social and organizational issues observed during the IFC. At that point, the first issue is related to the *network selection rules of airlines*. The IFC is enabled through the airlines to the passengers. At that point, the airline can choose different aeronautical network types according to the position and capability of the aircraft. More clearly, if an aircraft moves through the ocean, it can connect to satellite or AANETs instead of an A2G network. Similar to this example, there are various conditions, and the airlines determine their policies according to these conditions. The airline-specific policies affect the connectivities of all aircraft by changing network capacities and loads. Additionally, the second issue is related to the *hardware supports of airlines* that also affects their policies for IFC. Here, three aeronautical network types require different hardware equipment, and aircraft connectivity is shaped according to the airlines' support. Another issue is related to the *security precautions of airlines* during the IFC. The IFC should be enabled to the aircraft without letting the malicious intruders since this risk is more observed with the increasing amount of data and system complexity. The final consideration is the *collision risk* between the aircraft. Here, the connectivity of aircraft should be established by also considering the connection status of others. Otherwise, the aircraft observe collision during the packet transfer.

V. FUTURE DIRECTIONS

In this article, we analyzed three main aeronautical network types for IFC. Firstly, we investigated the state-of-the-art for the two dominating aeronautical network types: satellite connectivity and A2G networks. By analyzing the state-of-the-art challenges of these solutions, we highlighted the necessity of AANETs. After that point, we gave our specific interest to the AANETs by investigating its particular characteristics and open research problems in a layered concept. It is important to note that this was the first work collecting all the aeronautical networking types under one comprehensive survey. Also, the AANET specific challenges were examined from a layered aspect for the first time with this survey.

Although the AANET is a novel solution for the IFC, it has specific challenges and characteristics, as this article investigates from a layered aspect. The challenges of AANETs are not satisfied with the terrestrial-based algorithms, which creates management-level complexities. The AANET should adapt to the ultra-dynamic and unstructured environment with the correct management style. Otherwise, this adaptation increases the complexity of AANET management by also creating packet transfer and delay problems. Therefore, to increase the efficiency of AANET, we should handle its complexity with correct management mechanisms.

At that point, the intelligent frameworks could be utilized based on the AI to overcome the link, network, and transport-level management complexities of AANETs. The utilization of AI in wireless networks is common in the industry and academia. However, AI-driven AANETs are the new and unexplored research area. We claim that the AI-based supervised, unsupervised, and reinforcement learning methodologies can ease the management of AANET. The ultra-dynamic characteristics of AANETs could be learned utilizing AI-based methods, and these experiences could be used during management decisions dynamically without any central node and entity. As future work, we first aim to investigate the utilization of AI-driven methodologies in AANETs. Also, we aim to propose AI-based management frameworks in data link, network, and transport layers of AANETs.

VI. CONCLUSION

With the increasing technology and passenger number, in-flight Internet connectivity becomes crucial during a flight. This connectivity also becomes an essential income for the airlines. For this reason, the IFC takes the attention of both industry and academia. The satellite and A2G networks are widely known aeronautical solutions to enable this connectivity. Additionally, the AANETs are started to be included in the literature as a new practical solution.

This survey first analyzes the satellite and A2G connectivities by investigating state-of-the-art. Then, we examine the AANETs by giving topological details, environment and mobility effects, and open research challenges.

LIST OF ACRONYMS AND ABBREVIATIONS

A-R	ADS-B Aided Geographic Routing.
A2G	Air-to-Ground.
AAC	Airline Administrative Control.
AANETs	Aeronautical Ad-hoc Networks.
ACARS	Aircraft Communications and Reporting System.
ACL	ATC Clearances Service.
ACM	ATC Communications Management Servic.
ADS-B	Automatic Dependent Surveillance-Broadcast.
AeroMACS	Aeronautical Mobile Airport Communication System.
AeroMRP	Aeronautical Multipath Reliable Protocol.
AI	Artificial Intelligence.
AMCS	ATC Microphone Check Service.
AOC	Aeronautical Operational Control.
AODV	Ad hoc On-Demand Distance Vector.
ARPAM	Ad-hoc Routing Protocol for Aeronautical Mobile Ad-Hoc Networks.
ATC	Air Traffic Control.
ATN	Aeronautical Telecommunication Network.
ATSC	Air Traffic Services.
B-GAN	Broadband Global Area Network.
CAGR	Compound Annual Growth Rate.
CDMA	Code Division Multiple Access.
CPDLC	Controller Pilot Data Link Communications.
CSMA	Carrier Sense Multiple Access.
DAMA	Demand Assigned Multiple Access.
DDVC	Dynamic Doppler Velocity Clustering.
DLDC	Dynamic Link Duration Clustering.
DLIC	Data Link Initiation Capability.

DMDR	Delay aware Multipath Doppler Routing.
DME	Distance Measuring Equipment.
DS-CDMA	Direct Sequence CDMA.
DSB-AM	Double Sideband and Amplitude Modulation.
ECC	Electronic Communications Commitee.
EHF	Extremely High Frequency.
EUROCONTROL	European Organisation for Safety of Air Navigation.
FAA	Federal Aviation Administration.
FANETs	Flying Ad-Hoc Networks.
FDD	Frequency Division Duplex.
FDMA	Frequency Division Multiple Access.
FOBREQ	Forward Best Request.
GEO	Geostationary Earth Orbit.
GLSR	Geographic Load Share Routing.
GMSK	Gaussian Minimum Shift Keying.
GPS	Global Positioning System.
GPSR	Greedy Perimeter Stateless Routing.
GRAA	Geographic Routing Protocol for Aircraft Ad Hoc Network.
GSM	Global System for Mobile Communications.
HF	High Frequency.
HFDL	High Frequency Data Link.
HSRP	Hierarchical Space Routing Protocol.
ICAO	International Civil Aviation Organization.
ICO	Intermediate Circular Orbit.
IDTA	Interference-based Distributed TDMA Algorithm.
IFC	In-Flight Connectivity.
IGW	Internet Gateway.
Inmarsat	International Maritime Satellite.
IP	Internet Protocol.
IPv6	Internet Protocol Version 6.
L-DACS	L-band Digital Aeronautical Communication System.
LAA	Licensed Assisted Access.
LEO	Low Earth Orbit.
LF	Low Frequency.
LLC	Logical Link Control.
LOS	Line-of-Sight.
LTE	Long Term Evolution.
MAC	Medium Access Control.
MEO	Medium Earth Orbit.
MF	Medium Frequency.
MQSPR	Multiple QoS Parameters-based Routing.
MUDOR	Multipath Doppler Routing.
NGMN	Next Generation Mobile Network.
NoDe-TBR	Node Density Trajectory Based Routing.
NTAR	Node Mobility and Traffic Load Aware Routing.
OFDM	Orthogonal Frequency Division Multiplexing.
OFDM-FDD	Orthogonal Frequency Division Multiplexing-Frequency Division Duplex.
OFDMA	Orthogonal Frequency Division Multiple Access.
PLAR	Path Link Availability Routing Protocol.
QoS	Quality of Service.
QoS-MUDOR	QoS Multipath Doppler Routing.
RF	Radio Frequency.
RGR	Reactive Greedy Reactive.
RP-CDMA	Random Packet Code Division Multiple Access.
RREP	Route reply.
RREQ	Route Request.
RSVP	Resource Reservation Protocols.
RTT	Round-Trip-Time.
RUDP	Reliable User Datagram Protocol.
SAeroRP	Secure AeroRP.
SDMA	Space Division Multiple Access.
SHF	Super High Frequency.
SINR	Signal to Interference plus Noise Ratio.
SPMA	Statistical Priority Multiple Access.
SSB-AM	Single Side-Band Amplitude Modulation.
TCAS	Traffic Collision Avoidance System.
TCP	Transmission Control Protocol.
TD-LTE	Time Division LTE.
TDD	Time Division Duplex.
TDMA	Time Division Multiple Access.
Tx/Rx	Transmit/Receive.
UAV	Unmanned Aerial Vehicles.
UDP	User Datagram Protocol.
UHF	Ultra High Frequency.
VDL	VHF Data Link.
VHF	Very High Frequency.
VLF	Very Low Frequency.
WiFi	Wireless Fidelity.
WiMAX	Worldwide Interoperability for Microwave Access.

REFERENCES

[1] *2036 Forecast Reveals Air Passengers Will Nearly Double to 7.8 Billion*, IATA, Montreal, QC, Canada, Oct. 2017.

[2] N. Gupta and A. Aggarwal, "Airborne internet-the internet in the air," in *Proc. 7th Int. Conf. Cloud Comput., Data Sci. Eng.*, 2017, pp. 441–444, doi: 10.1109/CONFLUENCE.2017.7943191.

[3] T. Bilen, P. J. Aydemir, A. E. Konu, and B. Canberk, "Customized K-means based topology clustering for aeronautical ad-hoc networks," in *Proc. 26th Int. Workshop Comput. Aided Modeling Design Commun. Links Netw. (CAMAD)*, 2021, pp. 1–5.

[4] *Fasten Your Seatbelts: In-Flight Connectivity Takes Off*, Deloitte, London, U.K., Jul. 2018.

[5] *Survey: Airlines Risk Losing Passengers Due to Poor Wi-Fi*, Honeywell, Charlotte, NC, USA, 2016.

[6] *In-Flight Wi-Fi: Why Smart Airlines Need Smart Solutions*, May 2016.

[7] *Challenges of Growth, Task 4: European Air Traffic in 2035*, Eurocontrol, Brussels, Belgium, 2013.

[8] *Passenger Connectivity Services to Surpass $5 Billion by 2025*, Euroconsult, Brussels, Belgium, 2016.

[9] *Sky High Connectivity*, SES, Betzdorf, Luxembourg, Sep. 2016.

[10] *Sky High Economics*, Inmarsat, London, U.K., Sep. 2017.

[11] T. Bilen and B. Canberk, "Learning-vector-quantization-based topology sustainability for clustered-AANETs," *IEEE Netw.*, vol. 35, no. 4, pp. 120–128, Jul. 2021.

[12] *ICAO*. Accessed: Oct. 1, 2021. [Online]. Available: https://www.icao.int

[13] *Eurocontrol*. Accessed: Oct. 1, 2021. [Online]. Available: https://www.eurocontrol.int/

[14] *FAA*. Accessed: Oct. 1, 2021. [Online]. Available: https://www.faa.gov/

[15] O. S. Oubbati, M. Atiquzzaman, P. Lorenz, M. H. Tareque, and M. S. Hossain, "Routing in flying ad hoc networks: Survey, constraints, and future challenge perspectives," *IEEE Access*, vol. 7, pp. 81057–81105, 2019.

[16] O. S. Oubbati, A. Lakas, F. Zhou, M. Günes, and M. B. Yagoubi, "A survey on position-based routing protocols for flying ad hoc networks (FANETs)," *Veh. Commun.*, vol. 10, pp. 29–56, Oct. 2017.

[17] I. Bekmezci, O. K. Sahingoz, and Ş. Temel, "Flying ad-hoc networks (FANETs): A survey," *Ad Hoc Netw.*, vol. 11, no. 3, pp. 1254–1270, 2013.

[18] S. Rezwan and W. Choi, "A survey on applications of reinforcement learning in flying ad-hoc networks," *Electronics*, vol. 10, no. 4, p. 449, 2021. [Online]. Available: https://www.mdpi.com/2079-9292/10/4/449

[19] D. S. Lakew, U. Sa'ad, N.-N. Dao, W. Na, and S. Cho, "Routing in flying ad hoc networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 1071–1120, 2nd Quart., 2020.

[20] E. Cruz, "A comprehensive survey in towards to future FANETs," *IEEE Latin Amer. Trans.*, vol. 16, no. 3, pp. 876–884, Mar. 2018.

[21] M. Y. Arafat, S. Poudel, and S. Moh, "Medium access control protocols for flying ad hoc networks: A review," *IEEE Sensors J.*, vol. 21, no. 4, pp. 4097–4121, Feb. 2021.

[22] K.-L. Yau, R. Md Noor, and M. Imran, "Routing schemes in FANETs: A survey," *Sensors*, vol. 20, no. 12, p. 38, 2019.

[23] M. A. Khan, A. Safi, I. M. Qureshi, and I. U. Khan, "Flying ad-hoc networks (FANETs): A review of communication architectures, and routing protocols," in *Proc. INTELLECT*, 2017, pp. 1–9.

[24] M. Qassab and Q. Ali, "A comprehensive survey on current literature, standards, applications and projects of self-organizing aerial ad hoc network (AANET) in smart cities," *Current Chin. Comput. Sci.*, vol. 1, p. 45, Feb. 2021.

[25] P. Kumar and S. Verma, "Routing protocols in airborne ad-hoc networks (AANETs) a study," *Int. J. Comput. Sci. Eng.*, vol. 7, no. 4, pp. 1107–1113, Apr. 2019.

[26] J. Zhang, T. Chen, S. Zhong, J. Wang, W. Zhang, X. Zuo, R. G. Maunder, and L. Hanzo, "Aeronautical *ad hoc* networking for the internet-above-the-clouds," *Proc. IEEE*, vol. 107, no. 5, pp. 868–911, May 2019.

[27] T. Bilen and B. Canberk, "Three-phased clustered topology formation for aeronautical ad-hoc networks," *Pervas. Mobile Comput.*, vol. 79, Oct. 2022, Art. no. 101513.

[28] M. Abo-Zeed, J. Din, I. Shayea, and M. Ergen, "Survey on land mobile satellite system: Challenges and future research trends," *IEEE Access*, vol. 7, pp. 137291–137304, 2019, doi: 10.1109/ACCESS.2019.2941900.

[29] H. Beljour, R. Hoffmann, G. Michael, J. Shields, I. Sumit, C. Swenson, and A. Willson, "Concept for an all-digital satellite communications earth terminal," in *Proc. MILCOM*, 2009, pp. 1–5, doi: 10.1109/MILCOM.2009.5379774.

[30] F. Leipold, D. Tassetto, and S. Bovelli, "Wireless in-cabin communication for aircraft infrastructure," *Telecommun. Syst.*, vol. 52, no. 2, pp. 1211–1232, 2013, doi: 10.1007/s11235-011-9636-8.

[31] R. Kerczewski, M. Meza, and O. Gupta, "Application of the iridium satellite system to aeronautical communications," in *Proc. Broadband Commun. Conf.*, 2008, pp. 1–8.

[32] *Implementation Manual for Iridium Satellite Communications Service*, May 2006.

[33] *Manual for Iridium Aeronautical Mobile Satellite (ROUTE) Service*, Oct. 2006.

[34] M. Sadiku, *Optical and Wireless Communications: Next Generation Networks* (Electrical Engineering & Applied Signal Processing). Boca Raton, FL, USA: CRC Press, 2018.

[35] E. Dinc, M. Vondra, S. Hofmann, D. Schupke, M. Prytz, S. Bovelli, M. Frodigh, J. Zander, and C. Cavdar, "In-flight broadband connectivity: Architectures and business models for high capacity air-to-ground communications," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 142–149, Aug. 2017, doi: 10.1109/MCOM.2017.1601181.

[36] W. Jun-lin and L. Chun-sheng, "Development and application of inmarsat satellite communication system," in *Proc. 1st Int. Conf. Instrum., Meas., Comput., Commun. Control*, 2011, pp. 619–621 doi: 10.1109/IMCCC.2011.159.

[37] S. Rani and S. Malhotra, "Comparative study of leo, meo & geo satellites," *Int. J. Res.*, vol. 1, no. 9, pp. 1181–1186, 2014.

[38] P. Banerjee, *Satellite Communication*. New Delhi, India: PHI Learning, 2017.

[39] F. Dimc, G. Baldini, and S. Kandeepan, "Experimental detection of mobile satellite transmissions with cyclostationary features," *Int. J. Satellite Commun. Netw.*, vol. 33, no. 2, pp. 163–183, 2015.

[40] W. H. Jones and M. de La Chapelle, "Connexion by Boeing/sup SM/-broadband satellite communication system for mobile platforms," in *Proc. Commun. Netw.-Centric Oper., Creating Inf. Force*, vol. 2, 2001, pp. 755–758.

[41] *Swiftbroadband: High-Speed, Ip-Based Voice and Data*, Inmarsat, London, U.K., 2014.

[42] *Introduction to Swiftbroadband, Version 5.0*, Inmarsat, London, U.K., 2011.

[43] R. Proesch, *Technical Handbook for Satellite Monitoring*. Norderstedt, Germany: Books on Demand, 2019.

[44] S. Cakaj, "The parameters comparison of the starlink leo satellites constellation for different orbital shells," *Frontiers Commun. Netw.*, vol. 2, pp. 1–15, May 2021.

[45] I. del Portillo Barrios, B. Cameron, and E. Crawley, "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband," *Acta Astronautica*, vol. 159, pp. 123–135, Mar. 2019.

[46] P. Secher, "Oneweb non-geostationary satellite system (LEO)," Tech. Rep., 2015.

[47] D. Minoli, *Innovations in Satellite Communications and Satellite Technology: The Industry Implications of DVB-S2X, High Throughput Satellites, Ultra HD, M2M, and IP*. Hoboken, NJ, USA: Wiley, 2015, doi: 10.1002/9781118984086.

[48] S. Panthi1, C. McLain, and J. King, "The exconnect broadband aero service," in *Proc. AIAA. Commun. Satellite Syst. Conf.*, 2013, p. 5621.

[49] *Aeronautical Broadband for Commercial Aviation: Evaluating the 2Ku Solution*, GoGo, Chicago, IL, USA, 2014.

[50] *Global Aero Terminal 5320 Dual-Band (Ka- and Ku-Band) Broadband Airborne Terminal*, ViaSat, Carlsbad, CA, USA, 2015.

[51] *The Use of the Frequency Bands 27.5–30.0 GHz and 17.3–20.2 GHz by Satellite Networks*, ECC, Uttar Pradesh, India, 2010.

[52] V. Chandrasekar, H. Fukatsu, and K. Mubarak, "Global mapping of attenuation at Ku- and Ka-band," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 10, pp. 2166–2176, Oct. 2003, doi: 10.1109/TGRS.2003.815973.

[53] G. Varrall, *5G Spectrum and Standards*. Norwood, MA, USA: Artech House, 2016.

[54] G. Sebestyen, S. Fujikawa, N. Galassi, and A. Chuchra, *Low Earth Orbit Satellite Design*. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-68315-7.

[55] V. Kharchenko, Y. Barabanov, and A. Grekhov, "Modelling of satellite-to-aircraft link for self-separation," *Transport*, vol. 28, pp. 361–367, Apr. 2013, doi: 10.3846/16484142.2013.864699.

[56] A. Hashim, F. Mahad, S. Idrus, and A. Supa'at, "Modeling and performance study of inter-satellite optical wireless communication system," in *Proc. Int. Conf. Photon.*, 2010, pp. 1–4, doi: 10.1109/ICP.2010.5604379.

[57] K. Karras, T. Kyritsis, M. Amirfeiz, and S. Baiotti, "Aeronautical mobile ad hoc networks," in *Proc. 14th Eur. Wireless Conf.*, 2008, pp. 1–6, doi: 10.1109/EW.2008.4623845.

[58] D. Kolev and M. Toyoshima, "Satellite-to-ground optical communications using small optical transponder (SOTA) received-power fluctuations," *Opt. Exp.*, vol. 25, p. 28319, Apr. 2017, doi: 10.1364/OE.25.028319.

[59] H. Kaushal, V. Jain, and S. Kar, "Ground-to-satellite optical communication link performance with spatial diversity in weak atmospheric turbulence," *Fiber Integr. Opt.*, vol. 29, pp. 315–340, Apr. 2010, doi: 10.1080/01468030.2010.491893.

[60] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 57–96, 1st Quart., 2017, doi: 10.1109/COMST.2016.2603518.

[61] M. Mukherjee, "Wireless communication-moving from rf to optical," in *Proc. 3rd Int. Conf. Comput. Sustain. Global Develop.*, 2016, pp. 788–795.

[62] S. A. Alliance, "How the seamless air alliance will collaborate to make in-flight broadband access out of this world," Tech. Rep., 2018.

[63] *Using Air-to-Ground LTE for In-Flight Ultra-Broadband*, Alcatel-Lucent, Paris, France, 2015.

[64] D. Medina, F. Hoffmann, S. Ayaz, and C. Rokitansky, "Topology characterization of high density airspace aeronautical ad hoc networks," in *Proc. Int. Conf. Mobile Ad Hoc Sensor Syst.*, 2008, pp. 295–304, doi: 10.1109/MAHSS.2008.4660016.

[65] T. Yata, Y. Yamamoto, K. Kimishima, M. Onishi, N. Yonemoto, K. Morioka, and Y. Sumiya, "Field trials for air-to-ground direct communication using LTE on VHF band," in *Proc. Conf. Antenna Meas. Appl.*, 2017, pp. 83–86, doi: 10.1109/CAMA.2017.8273484.

[66] M. Sakamoto and S. Kawato, "Four-dimensional network simulation of direct air to ground lte networks," in *Proc. 1st Int. Workshop Link Syst. Level Simulations*, 2016, pp. 1–6, doi: 10.1109/IWSLS.2016.7801575.

[67] T. Bilen, T. Q. Duong, and B. Canberk, "Optimal eNodeB estimation for 5G intra-macrocell handover management," in *Proc. 12th ACM Symp. QoS Secur. Wireless Mobile Netw.*, New York, NY, USA, Nov. 2016, pp. 1–5, doi: 10.1145/2988272.2988284.

[68] M. Vondra, E. Dinc, and C. Cavdar, "Coordinated resource allocation scheme for 5G direct air-to-ground communication," in *Proc. 24th Eur. Wireless Conf.*, 2018, pp. 1–7.

[69] T. Bilen and B. Canberk, "Overcoming 5G ultra-density with game theory: Alpha-beta pruning aided conflict detection," *Pervas. Mobile Comput.*, vol. 63, Oct. 2020, Art. no. 101133.

[70] *Wireless 4 Air—Seamless Connectivity for Aircraft, Flying Cars and Drones*, ICARO-EU, Berlin, Germany, 2016.

[71] M. Vondra, M. Ozger, D. Schupke, and C. Cavdar, "Integration of satellite and aerial communications for heterogeneous flying vehicles," *IEEE Network*, vol. 32, no. 5, pp. 62–69, Apr. 2018, doi: 10.1109/MNET.2018.1800055.

[72] C. Cavdar, D. Gera, S. Hofmann, D. Schupke, A. Ghosh, and A. Nordlow, "Demonstration of an integrated 5G network in an aircraft cabin environment," in *Proc. IEEE/AIAA 37th Digit. Avionics Syst. Conf. (DASC)*, 2018, pp. 1–10, doi: 10.1109/DASC.2018.8569540.

[73] M. Vondra, E. Dinc, M. Prytz, M. Frodigh, D. Schupke, S. Hofmann, and C. Cavdar, "Performance study on seamless DA2GC for aircraft passengers toward 5G," *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 194–201, Nov. 2017, doi: 10.1109/MCOM.2017.1700188.

[74] *5g White Paper*, NGMN, Frankfurt am Main, Germany, Feb. 2015.

[75] J. P. Rula, J. Newman, F. E. Bustamante, A. M. Kakhki, and D. Choffnes, "Mile high WiFi: A first look at in-flight internet connectivity," in *Proc. World Wide Web Conf.*, 2018, pp. 1449–1458, doi: 10.1145/3178876.3186057.

[76] *Anatomy of an Air-to-Ground (ATG) Network*, GoGo, Chicago, IL, USA, 2015.

[77] D. Medina, F. Hoffmann, S. Ayaz, and C. Rokitansky, "Feasibility of an aeronautical mobile ad hoc network over the north atlantic corridor," in *Proc. 5th Annu. Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw.*, 2008, pp. 109–116, doi: 10.1109/SAHCN.2008.23.

[78] A. Gusarov, "Aircraft antenna array for seamless direct air-to-ground communication system," Ph.D. dissertation, KTH Elect. Eng., Stockholm, Sweden, 2016.

[79] *The Harmonised Use of Broadband Direct Air-to-Ground Communications (DA2GC) Systems in the Frequency Band 1900-1920 MHz*, ECC, Chennai, India, Jul. 2015.

[80] *The Harmonised Use of Broadband Direct Air-to-Ground Communications (DA2GC) Systems in the Frequency Band 5855-5875 MHz*, ECC, Chennai, India, Jul. 2015.

[81] *Broadband Direct Air-to-Ground Communications: Equipment Operating in the 1 900 MHz to 1 920 MHz and 5 855 MHz to 5 875 MHz Frequency Bands: Beamforming Antennas: Harmonised Standard Covering the Essential Requirements of Article 3.2 of Directive 2014/53/eu*, ETSI, Sophia Antipolis, France, Oct. 2017.

[82] I. Kabashkin, "Resilient communication network of air traffic management system," in *Proc. Adv. Wireless Opt. Commun. (RTUWO)*, 2016, pp. 156–160, doi: 10.1109/RTUWO.2016.7821875.

[83] *Procedures for Air Navigation Services Air Traffic Management*, International Civil Aviation Organization, Montreal, QC, Canada, 2007.

[84] M. Schnell, U. Epple, D. Shutin, and N. Schneckenburger, "'LDACS: Future aeronautical communications for air-traffic management," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 104–110, May 2016, doi: 10.1109/MCOM.2014.6815900.

[85] *Study Item on VHF Data Link Mode 2 Ground-Based Equipment Standardization Optimization*, ETSI, : Sophia Antipolis, France, 2018.

[86] T. Bilen, K. Ayvaz, and B. Canberk, "Qos-based distributed flow management in software defined ultra-dense networks," *Ad Hoc Netw.*, vol. 78, pp. 24–31, Oct. 2018.

[87] S. Plass, *Future Aeronautical Communications*. London, U.K.: IntechOpen, 2011.

[88] T. G. N. Maeurer and C. Schmitt, "L-band digital aeronautical communications system (LDACS) document," Tech. Rep., 2019.

[89] C. Rihacek, B. Haindl, P. Fantappie, and S. Pieratelli, "L-band digital aeronautical communications system (LDACS) activities in SESAR2020," in *Proc. Integr. Commun., Navigat., Surveill. Conf.*, 2018, pp. 1–4, doi: 10.1109/ICNSURV.2018.8384880.

[90] S. Ayaz, F. Hoffmann, R. German, and F. Dressler, "Analysis of deficit round robin scheduling for future aeronautical data link," in *Proc. IEEE 22nd Int. Symp. Pers., Indoor Mobile Radio Commun.*, 2011, pp. 1809–1814, doi: 10.1109/PIMRC.2011.6139820.

[91] N. Neji, R. de Lacerda, A. Azoulay, T. Letertre, and O. Outtier, "Survey on the future aeronautical communication system and its development for continental communications," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 182–191, Jan. 2013, doi: 10.1109/TVT.2012.2207138.

[92] B. Wang, Y. Chang, and H. Li, "DME interference analysis in aeronautical LTE networks," in *Proc. WiSPNET*, 2016, pp. 1727–1731, doi: 10.1109/WiSPNET.2016.7566434.

[93] (2009). *L-DACS2 Transmitter and Receiver Prototype Equipment Specifications: Deliverable D3*. [Online]. Available: https://www.eurocontrol.int/

[94] *updated Ldacs1 System Specification*, Sesar, New York, NY, USA, 2004.

[95] p. Gibson and E. Mitchell, "ACARS: Timeless tech for the connected aircraft age," in *Proc. 7th Int. Wireless Commun. Mobile Comput. Conf.*, 2017, pp. 1–5.

[96] G. Bartoli, R. Fantacci, and D. Marabissi, "AeroMACS: A new perspective for mobile airport communications and services," *IEEE Wireless Commun.*, vol. 20, no. 6, pp. 44–50, Dec. 2013, doi: 10.1109/MWC.2013.6704473.

[97] M. Paolini and S. Fili, *AeroMACS: A Common Platform for Air Traffic Management Applications*. Beijing, China: WiMAX Forum, 2015.

[98] J. Budinger and E. Hall, "Aeronautical mobile airport communications system (AeroMACS)," Tech. Rep., 2011, doi: 10.5772/30292.

[99] D. Pareit, B. Lannoo, I. Moerman, and P. Demeester, "The history of WiMAX: A complete survey of the evolution in certification and standardization for IEEE 802.16 and WiMAX," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 1183–1211, 4th Quart., 2012, doi: 10.1109/SURV.2011.091511.00129.

[100] *Data Link Services (DLS) System: Community Specification for Application Under the Single European sky Interoperability Regulation EC 552/2004: Requirements for Ground Constituents and System Testing*, ETSI, Sophia Antipolis, France, 2011.

[101] *Manual for the ATN using IPS standards and protocols*, document 9896-an/469, ICAO, 2009.

[102] *Aircom Datalink VDL and ATN Services Data Sheet*, 2015.

[103] M. S. B. Mahmoud, A. Pirovano, and N. Larrieu, "Aeronautical communication transition from analog to digital data: A network security survey," *Comput. Sci. Rev.*, vols. 11–12, pp. 1–29, Jul. 2014, doi: 10.1016/j.cosrev.2014.02.001.

[104] C. Yoo, B. Song, A. Cho, and S. Koo, "Ground and flight test of ADS-B system in Goheung area, in *Proc. Int. Workshop Digit. Commun. Enhanced Surveill. Aircr. Veh. (TIWDC/ESAV)*, 2014, pp. 92–95, doi: 10.1109/TIWDC-ESAV.2014.6945455.

[105] (2012). *NextGen*.[Online]. Available: http://gadc.aero/wp-content/uploads/2013/11/GR0042-WPR_NextGen-White-Paper_Rev-B.pdf

[106] *Integrated ADS-B Systems Incorporating L-Band and VHF Technologies*, Aeronautical Mobile Communications, Fort Wayne, IN, USA, 2002.

[107] *Airborne Collision Avoidance System (ACAS) Manual*, ICAO, Montreal, QC, Canada, 2006.

[108] SESAR. (2019). *Showcasing Progress of Future Datalink Solutions*. [Online]. Available: https://www.sesarju.eu/news/showcasing-progress-future-datalink-solutions

[109] F. Hoffmann, D. Medina, and A. Wolisz, ''Protocol architecture analysis for internet connectivity in aeronautical ad hoc networks,'' in *Proc. 29th Digit. Avionics Syst. Conf.*, 2010, pp. 1–12, doi: 10.1109/DASC.2010.5655370.

[110] C. Shi, Q. Ren, B. Zheng, and Y. Liu, ''Analysis of node density and probability of forming a network in military aeronautical ad hoc networks,'' in *Proc. Int. Conf. Microw. Millim. Wave Technol.*, vol. 4, 2008, pp. 1980–1982, doi: 10.1109/ICMMT.2008.4540878.

[111] F. Hoffmann, D. Medina, and A. Wolisz, ''Two-step delay based internet gateway selection scheme for aeronautical ad hoc networks,'' in *Proc. 20th Int. Symp. Pers., Indoor Mobile Radio Commun.*, 2009, pp. 2638–2642, doi: 10.1109/PIMRC.2009.5449871.

[112] J. Li, E. Gong, Z. Sun, L. Li, and H. Xie, ''Fault-tolerant topology control in aeronautical ad hoc networks,'' in *Proc. Int. Conf. Mechatronics Automat.*, 2014, pp. 368–372, doi: 10.1109/ICMA.2014.6885725.

[113] M. S. Ben Mahmoud, C. Guerber, N. Larrieu, A. Pirovano, and J. Radzik, *Aeronautical Air Ground Data Link Communications*. Hoboken, NJ, USA: Wiley, 2014, doi: 10.1002/9781119006954.

[114] A. Rana and V. Kumar, ''Aircraft ad-hoc network (AANET),'' *Int. J. Innov. Res. Comput. Commun. Eng.*, vol. 3, pp. 6679–6684, Apr. 2019.

[115] T. Bilen and B. Canberk, ''Binary context tree based middleware for next generation context aware networks,'' in *Proc. 3rd Int. Conf. Future Internet Things Cloud*, 2015, pp. 93–99.

[116] *Study on Channel Model for Frequency Spectrum Above 6 GHz*, ETSI, Sophia Antipolis, France, 2017.

[117] U. Kesavan, M. R. Islam, K. Abdullah, and A. R. Tharek, ''Rain attenuation prediction for higher frequencies in microwave communication using frequency scaling technique,'' in *Proc. Int. Conf. Comput. Commun. Eng.*, 2014, pp. 217–219, doi: 10.1109/ICCCE.2014.69.

[118] *Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems*, ITU-R, Geneva, Switzerland, 2017.

[119] *Recommendation ITU-R 838-3, Specific Attenuation Model for Rain for Use in Prediction Methods*, ITU-R, Geneva, Switzerland, 2015.

[120] *Attenuation Due to Clouds and Fog*, document 840-5, ITU-R, 2012.

[121] T. A. Alawadi, ''Investigation of the effects of cloud attenuation on satellite communication systems,'' Ph.D. dissertation, Dept. Eng. Phys. School Eng., Cranfield Univ., Bedford, U.K., 2012.

[122] J. Yan, C. Hua, C. Chen, and X. Guan, ''The capacity of aeronautical adhoc networks,'' *Wireless Netw.*, vol. 20, no. 7, pp. 2123–2130, 2014, doi: 10.1007/s11276-014-0737-7.

[123] J. Li, L. Lei, W. Liu, Y. Shen, and G. Zhu, ''An improved semi-Markov smooth mobility model for aeronautical ad hoc networks,'' in *Proc. 8th Int. Conf. Wireless Commun., Netw. Mobile Comput.*, 2012, pp. 1–4, doi: 10.1109/WiCOM.2012.6478420.

[124] S. Alam, H. Abbass, and M. Barlow, ''Atoms: Air traffic operations and management simulator,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 2, pp. 209–225, Jan. 2008, doi: 10.1109/TITS.2008.922877.

[125] S. Ghosh and A. Nayak, ''Multi-dimensional clustering and network monitoring system for aeronautical ad hoc networks,'' in *Proc. Int. Conf. Ubiquitous Future Netw.*, 2015, pp. 772–777, doi: 10.1109/ICUFN.2015.7182647.

[126] D. Zhong, Y. Zhu, T. You, and J. Kong, ''Topology control mechanism based on link available probability in aeronautical ad hoc network,'' *J. Netw.*, vol. 9, no. 12, p. 3356, Dec. 2015, doi: 10.4304/jnw.9.12.3356-3365.

[127] E. Sakhaee and A. Jamalipour, ''The global in-flight internet,'' *IEEE J. Sel. Areas Commun.*, vol. 24, no. 9, pp. 1748–1757, Sep. 2006, doi: 10.1109/JSAC.2006.875122.

[128] E. Sakhaee and A. Jamalipour, ''Aerouter—A graphical simulation tool for routing in aeronautical systems,'' in *Proc. IEEE Wireless Commun. Netw. Conf.*, May 2005, pp. 2506–2511, doi: 10.1109/WCNC.2005.1424908.

[129] N. My, Y. Miyanaga, and C. Saivichit, ''Connectivity analytical modelling for a single flight path ad hoc aeronautical network,'' in *Proc. Int. Conf. Elect. Eng./Electron., Comput., Telecommun. Inf. Technol.*, 2010, pp. 51–55.

[130] H. Zhang, X. Chen, B. Zheng, and Y. Wang, ''Analysis of connectivity requirement for aeronautical ad hoc networks,'' in *Proc. Int. Conf. Electron. Mech. Eng. Inf. Technol.*, vol. 8, 2011, pp. 3943–3946, doi: 10.1109/EMEIT.2011.6023090.

[131] H. Li, B. Yang, C. Chen, and X. Guan, ''Connectivity of aeronautical ad hoc networks,'' in *Proc. Globecom Workshops*, 2010, pp. 1788–1792, doi: 10.1109/GLOCOMW.2010.5700249.

[132] J. Yan, G. Song, H. Li, C. Hua, C. Chen, and X. Guan, ''Critical transmission range for connectivity in aeronautical ad-hoc networks,'' in *Proc. 10th World Congr. Intell. Control Automat.*, 2012, pp. 4446–4451, doi: 10.1109/WCICA.2012.6359230.

[133] Y. Wang, M. C. Erturk, J. Liu, I. Ra, R. Sankar, and S. Morgera, ''Throughput and delay of single-hop and two-hop aeronautical communication networks,'' *J. Commun. Netw.*, vol. 17, no. 1, pp. 58–66, 2015, doi: 10.1109/JCN.2015.000010.

[134] Y. Wang, M. Erturk, H. Arslan, R. Sankar, and S. Morgera, ''Throughput analysis in aeronautical data networks,'' in *Proc. 12th Annu. Wireless Microw. Technol. Conf.*, Apr. 2011, pp. 1–8, doi: 10.1109/WAMICON.2011.5872890.

[135] D. Medina, F. Hoffmann, F. Rossetto, and C. Rokitansky, ''Routing in the airborne internet,'' in *Proc. Integr. Commun., Navigat., Surveill. Conf.*, 2010, pp. 1–10, doi: 10.1109/ICNSURV.2010.5503320.

[136] F. Hoffmann, D. Medina, and A. Wolisz, ''Optimization of routing and gateway allocation in aeronautical ad hoc networks using genetic algorithms,'' in *Proc. 7th Int. Wireless Commun. Mobile Comput. Conf.*, 2011, pp. 1391–1396, doi: 10.1109/IWCMC.2011.5982741.

[137] F. Hoffmann, D. Medina, and A. Wolisz, ''Joint routing and scheduling in mobile aeronautical ad hoc networks,'' *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, pp. 2700–2712, Apr. 2013, doi: 10.1109/TVT.2013.2246877.

[138] N. Kato, Z. M. Fadlullah, F. Tang, B. Mao, S. Tani, A. Okamura, and J. Liu, ''Optimizing space-air-ground integrated networks by artificial intelligence,'' *IEEE Wireless Commun.*, vol. 26, no. 4, pp. 140–147, Jan. 2019, doi: 10.1109/MWC.2018.1800365.

[139] H. D. Tu and S. Shimamoto, ''A proposal of relaying data in aeronautical communication for oceanic flight routes employing mobile ad-hoc network,'' in *Proc. 1st Asian Conf. Intell. Inf. Database Syst.*, 2009, pp. 436–441, doi: 10.1109/ACIIDS.2009.91.

[140] J. Gronkvist, J. Karlsson, U. Sterner, J. Nilsson, and A. Hansson, ''Adaptation delay and its impact on application performance for tdma ad hoc networks,'' in *Proc. 11th Annu. Medit. Ad Hoc Netw. Workshop*, 2012, pp. 55–60, doi: 10.1109/MedHocNet.2012.6257123.

[141] J. Li, E. Gong, Z. Sun, L. Li, and H. Xie, ''An interference-based distributed TDMA scheduling algorithm for aeronautical ad hoc networks,'' in *Proc. Int. Conf. Cyber-Enabled Distrib. Comput. Knowl. Discovery*, 2013, pp. 453–460, doi: 10.1109/CyberC.2013.84.

[142] Q. Qiu, Z. Fang, and C. Gong, ''Study on key techniques of aeronautical ad hoc network MAC and network layer,'' in *Proc. Asia–Pacific Int. Symp. Aerosp. Technol.*, 2015, pp. 280–291, doi: 10.1016/j.proeng.2014.12.536.

[143] Q. Qiu, Z. Fang, and C. Gong, ''Study on key techniques of aeronautical ad hoc network MAC and network layer,'' *Proc. Eng.*, vol. 99, pp. 280–291, Jan. 2015, doi: 10.1016/j.proeng.2014.12.536.

[144] F. Besse, A. Pirovano, F. Garcia, and J. Radzik, ''Interference estimation in an aeronautical ad hoc network,'' in *Proc. AIAA/IEEE Digit. Avionics Syst. Conf.*, Oct. 2016, pp. 1–6, doi: 10.1109/DASC.2011.6095908.

[145] F. Besse, F. Garcia, A. Pirovano, and J. Radzik, ''Wireless ad hoc networks access for aeronautical communications,'' in *Proc. AIAA Int. Commun. Satell. Syst. Conf* 2010, p. 8795, doi: 10.2514/6.2010-8795.

[146] *Antares Communication Standard Design Definition File, Iris Technical Note*, Indra, Chennai, India, 2013.

[147] Q. Vey, A. Pirovano, and J. Radzik, ''Performance analysis of routing algorithms in AANet with realistic access layer,'' in *Communication Technologies for Vehicles*, J. Mendizabal, M. Berbineau, A. Vinel, S. Pfletschinger, H. Bonneville, A. Pirovano, S. Plass, R. Scopigno, and H. Aniss, Eds. Cham, Switzerland: Springer, 2016, pp. 175–186.

[148] *FlightRadar*. Accessed: Oct. 1, 2021. [Online]. Available: https://www.flightradar24.com/

[149] Y. Sun, E. Belding, and C. Perkins, ''Internet connectivity for ad hoc mobile networks,'' *Int. J. Wireless Inf. Netw.*, vol. 9, no. 2, pp. 75–88, Aug. 2002, doi: 10.1023/A:1015399632291.

[150] C.-F. Huang, H.-W. Lee, and Y.-C. Tseng, ''A two-tier heterogeneous mobile ad hoc network architecture and its load-balance routing problem,'' *Mobile Netw. Appl.* vol. 9, pp. 2163–2167, Aug. 2003, doi: 10.1109/VETECF.2003.1285912.

[151] K. Buchter, ''Availability of aeronautical ad-hoc network in different global air transport fleet scenarios,'' in *Proc. Gen. Assem. Sci. Symp. Int. Union Radio Sci.*, 2017, pp. 1–4.

[152] R. Brannstrom, C. Ahlund, and A. Zaslavsky, ''Maintaining gateway connectivity in multi-hop ad hoc networks,'' in *Proc. Conf. Local Comput. Netw. Anniversary*, 2005, pp. 682–689, doi: 10.1109/LCN.2005.86.

[153] E. Sakhaee and A. Jamalipour, "Stable clustering and communications in pseudolinear highly mobile ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3769–3777, Nov. 2008, doi: 10.1109/TVT.2008.919606.

[154] M. Royer, F. Garcia, and A. Pirovano, "An enhanced 1-hop clustering algorithm for Publish/Subscribe systems in AANETS," in *Proc. IEEE/AIAA 34th Digit. Avionics Syst. Conf. (DASC)*, Sep. 2015, pp. 1–6, doi: 10.1109/DASC.2015.7311373.

[155] F. Shi, Y. Shi, and L. Lai, "A clustering algorithm of ad-hoc network based on honeycomb division," in *Proc. IEEE Int. Conf. Granular Comput.*, Nov. 2011, pp. 863–866, doi: 10.1109/GRC.2011.6122549.

[156] Q. Vey, A. Pirovano, J. Radzik, and F. Garcia, "Aeronautical ad hoc network for civil aviation," in *Proc. Int. Workshop Commun. Technol. Veh.*, 2014, pp. 81–93, doi: 10.1007/978-3-319-06644-8.

[157] Y. Wang, H. Arslan, R. Sankar, I. Ra, and S. Morgera, "Throughput and delay analysis in aeronautical data networks," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, 2012, pp. 771–775, doi: 10.1109/ICCNC.2012.6167527.

[158] D. Medina, F. Hoffmann, F. Rossetto, and C. Rokitansky, "North atlantic inflight internet connectivity via airborne mesh networking," in *Proc. Veh. Technol. Conf.*, 2011, pp. 1–5.

[159] D. Zhong, Y. Wang, Y. Zhu, and T. You, "An aeronautical ad hoc network routing protocol based on air vehicles movement features," in *Proc. 22nd Int. Conf. Appl. Electromagn. Commun.*, 2016, pp. 1–6, doi: 10.1109/ICECom.2016.7843898.

[160] A. Durresi, V. Paruchuri, L. Barolli, and R. Jain, "Air to air communication protocol," in *Proc. Aerosp. Conf.*, 2006, p. 8, doi: 10.1109/AERO.2006.1655883.

[161] D. Zhong, "A new data transmission mechanism in aeronautical ad hoc network," in *Proc. Int. Conf. Big Data Smart Comput.*, 2014, pp. 255–260, doi: 10.1109/BIGCOMP.2014.6741447.

[162] M. Iordanakis, D. Yannis, K. Karras, G. Bogdos, G. Dilintas, M. Amirfeiz, G. Colangelo, and S. Baiotti, "Ad-hoc routing protocol for aeronautical mobile ad-hoc networks," in *Proc. 5th Int. Symp. Commun. Syst., Netw. Digit. Signal Process.*, Jul. 2006, pp. 1–5.

[163] K. Peters, A. Jabbar, E. K. Cetinkaya, and J. P. G. Sterbenz, "A geographical routing protocol for highly-dynamic aeronautical networks," in *Proc. Wireless Commun. Netw. Conf.*, 2011, pp. 492–497, doi: 10.1109/WCNC.2011.5779182.

[164] A. Swidan, S. Khattab, Y. Abouelseoud, and H. Elkamchouchi, "A secure geographical routing protocol for highly-dynamic aeronautical networks," in *Proc. Military Commun. Conf.*, 2015, pp. 708–713, doi: 10.1109/MILCOM.2015.7357527.

[165] F. Tchakountio and R. Ramanathan, "Anticipatory routing for highly mobile endpoints," in *Proc. Workshop Mobile Comput. Syst. Appl.*, 2004, pp. 94–100, doi: 10.1109/MCSA.2004.7.

[166] F. Tchakountio and R. Ramanathan, "Tracking highly mobile endpoints," in *Proc. 4th ACM Int. Workshop Wireless Mobile Multimedia*, 2001, pp. 83–94, doi: 10.1145/605991.606003.

[167] M. Mauve, J. Widmer, and H. Hartenstein, "A survey on position-based routing in mobile ad hoc networks," *IEEE Netw.*, vol. 15, no. 6, pp. 30–39, Apr. 2001, doi: 10.1109/65.967595.

[168] R. Shirani, M. St-Hilaire, T. Kunz, Y. Zhou, J. Li, and L. Lamont, "The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks," in *Proc. 9th Annu. Commun. Netw. Services Res. Conf.*, 2011, pp. 161–166, doi: 10.1109/CNSR.2011.31.

[169] R. Shirani, M. St-Hilaire, T. Kunz, Y. Zhou, J. Li, and L. Lamont, "Combined reactive-geographic routing for unmanned aeronautical ad-hoc networks," in *Proc. 8th Int. Wireless Commun. Mobile Comput. Conf.*, 2012, pp. 820–826, doi: 10.1109/IWCMC.2012.6314310.

[170] Y. Li, M. St-Hilaire, and T. Kunz, "Enhancements to reduce the overhead of the reactive-greedy-reactive routing protocol for unmanned aeronautical ad-hoc networks," in *Proc. Int. Conf. Wireless Commun., Netw. Mobile Comput.*, 2012, pp. 1–4, doi: 10.1109/WiCOM.2012.6478515.

[171] M. Kardoust, M. R. Khayyambashi, and A. Bohlooli, "Introducing a method for improving the performance of routing algorithms in unmanned aeronautical ad-hoc networks," in *Proc. 9th Int. Conf. Inf. Knowl. Technol. (IKT)*, 2017, pp. 85–92, doi:10.1109/IKT.2017.8258623.

[172] Q. Vey, S. Puechmorel, A. Pirovano, and J. Radzik, "Routing in aeronautical ad-hoc networks," in *Proc. IEEE/AIAA 35th Digit. Avionics Syst. Conf. (DASC)*, 2016, pp. 1–10, doi: 10.1109/DASC.2016.7777989.

[173] D. W. Seo, S. H. Kim, and Y. J. Suh, "System integration of GPSR and ADS-B for aeronautical ad hoc networks," in *Proc. Mil. Commun. Conf.*, 2008, pp. 1–6, doi: 10.1109/MILCOM.2008.4753120.

[174] M. S. B. Mahmoud and N. Larrieu, "An ADS-B based secure geographical routing protocol for aeronautical ad hoc networks," in *Proc. 37th Annu. Comput. Softw. Appl. Conf. Workshops*, 2013, pp. 556–562, doi: 10.1109/COMPSACW.2013.74.

[175] Q. Zhou, W. Gu, J. Li, Q. Sun, and F. Yang, "A topology aware routing protocol based ADS-B system for aeronautical ad hoc networks," in *Proc. Int. Conf. Wireless Commun., Netw. Mobile Comput.*, 2012, pp. 1–4, doi: 10.1109/WiCOM.2012.6478379.

[176] W. Gu, J. Li, M. Lv, Q. Sun, and F. Yang, "Delay aware multipath Doppler routing in aeronautical ad hoc networks," in *Proc. IEEE Int. Conf. Comput. Sci. Eng.*, 2011, pp. 251–255, doi: 10.1109/CSE.2011.53.

[177] J. Zhou, L. Lei, W. Liu, and J. Tian, "A simulation analysis of nodes mobility and traffic load aware routing strategy in aeronautical ad hoc networks," in *Proc. 9th Int. Bhurban Conf. Appl. Sci. Technol.*, 2012, pp. 423–426, doi: 10.1109/IBCAST.2012.6177592.

[178] Q. Luo and J. Wang, "Multiple QOS parameters-based routing for civil aeronautical ad hoc networks," *IEEE Internet Things J.*, vol. 4, no. 3, pp. 804–814, Jul. 2017, doi: 10.1109/JIOT.2017.2669993.

[179] E. Sakhaee, A. Jamalipour, and N. Kato, "Multipath Doppler routing with QOS support in pseudo-linear highly mobile ad hoc networks," in *Proc. Int. Conf. Commun.*, vol. 8, 2006, pp. 3566–3571, doi: 10.1109/ICC.2006.255625.

[180] S. Hyeon, K. Kim, and S. Yang, "A new geographic routing protocol for aircraft ad hoc networks," in *Proc. 29th Digit. Avionics Syst. Conf.*, 2010, pp. 1–5, doi: 10.1109/DASC.2010.5655476.

[181] Nguyen Thi Xuan My, Y. Miyanaga, and C. Saivichit, "Link longevity-based routing mechanisms for aviation ad hoc network," in *Proc. 16th Int. Workshop Comput. Aided Modeling Design of Commun. Links Netw. (CAMAD)*, 2011, pp. 46–50, doi: 10.1109/CAMAD.2011.5941115.

[182] H. Che, P. M. L. Chan, and Y. F. Hu, "Design and analysis of QOS-enabled handover algorithm for aeronautical communication systems," in *Proc. 2nd Int. Symp. Wireless Commun. Syst.*, 2005, pp. 724–728, doi: 10.1109/ISWCS.2005.1547802.

[183] D. Medina, F. Hoffmann, F. Rossetto, and C. Rokitansky, "A geographic routing strategy for north atlantic in-flight internet access via airborne mesh networking," *IEEE/ACM Trans. Netw.*, vol. 20, no. 4, pp. 1231–1244, Apr. 2012, doi: 10.1109/TNET.2011.2175487.

[184] S. Ayaz, F. Hoffmann, C. Sommer, R. German, and F. Dressler, "Performance evaluation of network mobility handover over future aeronautical data link," in *Proc. Global Telecommun. Conf.*, 2010, pp. 1–6, doi: 10.1109/GLOCOM.2010.5684106.

[185] D. Wang, Y. Wang, S. Dong, G. Huang, J. Liu, and W. Gao, "Exploiting dual connectivity for handover management in heterogeneous aeronautical network," *IEEE Access*, vol. 7, pp. 62938–62949, 2019, doi: 10.1109/ACCESS.2019.2916920.

[186] M. Muhammad and M. Berioli, *Transport Protocol for Future Aeronautics*. London, U.K.: IntechOpen, 2011, doi: 10.5772/28455.

[187] J. Fang and M. Liu, "Design and implementation of embedded RUDP," in *Proc. 2nd Int. Conf. Netw. Distrib. Comput.*, 2011, pp. 1–9.

[188] Q. Luo and J. Wang, "FRUDP: A reliable data transport protocol for aeronautical ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 257–267, Apr. 2018, doi: 10.1109/JSAC.2018.2804099.

[189] K. Pathapati, T. Nguyen, J. Rohrer, and J. Sterbenz, "Performance analysis of the aerotp transport protocol for highly-dynamic airborne telemetry networks," in *Proc. Int. Telemetering Conf.*, 2011, pp. 1–4.

[190] M. Alenazi, S. Gogi, D. Zhang, E. Cetinkaya, J. Rohrer, and J. Sterbenz, "ANTP protocol suite software implementation architecture in Python," in *Proc. Int. Found. Telemetering*, 2015, pp. 1–11.

[191] F. Besse, A. Pirovano, F. Garcia, and J. Radzik, "Aeronautical ad hoc networks: A new datalink for ATM," in *Proc. 9th Innov. Res. Workshop Exhib.*, 2017, p. 10.

[192] Q. Luo, J. Wang, and S. Liu, "AEROMRP: A multipath reliable transport protocol for aeronautical ad hoc networks," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3399–3410, Apr. 2019, doi: 10.1109/JIOT.2018.2883736.

[193] J. Li, E. Gong, Z. Sun, W. Liu, and H. Xie, "AEROMTP: A fountain code-based multipath transport protocol for airborne networks," *Chin. J. Aeronaut.*, vol. 28, no. 4, pp. 1147–1162, 2015.

[194] L. Liu, "Performance evaluation of direct air-to-ground communication using new radio (5G)," Ph.D. dissertation, KTH Elect. Eng., Stockholm, Sweden, 2017.

[195] *Advisory Circular*, FA Administration, London, U.K., 2015.

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