CONTRIBUTED PAPER

Aeronautical *Ad Hoc* Networking for the Internet-Above-the-Clouds

This paper provides an overview of ad hoc aeronautical networking solutions by characterizing the associated scenarios, requirements, and challenges.

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ABSTRACT | The engineering vision of relying on the "smart sky" for supporting air traffic and the "internet-above-the-clouds" for in-flight entertainment has become imperative for the future aircraft industry. Aeronautical *ad hoc* networking (AANET) constitutes a compelling concept for providing broadband communications above clouds by extending the coverage of air-to-ground (A2G) networks to oceanic and remote airspace via autonomous and self-configured wireless networking among commercial passenger airplanes. The AANET concept may be viewed as a new member of the family of mobile *ad hoc* networks (MANETs) in action above the clouds. However, AANETs have more dynamic topologies, larger and more variable geographical network size, stricter security requirements, and more hostile transmission conditions. These specific characteristics lead to more grave challenges in aircraft mobility modeling, aeronautical channel modeling, and interference mitigation as well as in network scheduling and routing. This paper provides an overview of AANET solutions by characterizing the associated scenarios, requirements, and challenges. Explicitly, the research addressing the key techniques of AANETs, such as their mobility models, network scheduling and routing, security, and interference, is reviewed. Furthermore, we also identify the remaining challenges associated with developing AANETs and present their prospective solutions as well as open issues. The design framework of AANETs and the key technical issues are investigated along with some recent research results. Furthermore, a range of performance metrics optimized in designing AANETs and a number of representative multiobjective optimization algorithms are outlined.

KEYWORDS | Aeronautical *ad hoc* network (AANET); air-to-air (A2A) communication; air-to-ground (A2G) communication; air-to-satellite (A2S) communication; flying *ad hoc* network (FANET); network topology; networking protocol.

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NOMENCLATURE

A2A	Air to air.
A2G	Air to ground.
A2S	Air to satellite.
AANET	Aeronautical *ad hoc* network.
ACARS	Aircraft communication addressing and reporting system.
ACAS	Airborne collision avoidance system.
ACM	Adaptive coding and modulation.
ADS	Automatic-dependent surveillance.
ADS-B	ADS broadcast.
ADS-C	ADS contract.
AeroMACS	Aeronautical mobile airport communication system.
AMACS	All-purpose multichannel aviation communication system.

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AOA	Angle of arrival.
ASAS	Airborne separation assurance system.
ATC	Air traffic control.
ATCT	ATC tower.
ATM	Air traffic management.
B-AMC	Broadband aeronautical multicarrier communications.
BER	Bit error ratio.
BS	Base station.
CCDF	Complementary cumulative distribution function.
CDMA	Code-division multiple access.
COMETS	Communications and broadcasting engineering test satellites.
CPFSK	Continuous-phase frequency-shift keying.
CR	Cognitive radio.
CRL	Communications research laboratory.
CRT	CR technology.
DL	Downlink.
EAN	European Aviation Network.
FAA	Federal Aviation Administration.
FANET	Flying *ad hoc* network.
FCI	Future communications infrastructure.
FDD	Frequency-duplex division.
FDOA	Frequency difference of arrival.
FM	Frequency modulation.
FSO	Free-space optical.
GMSK	Gaussian minimum-shift keying.
GPS	Global positioning system.
GS	Ground station.
GSM	Global system for mobile communications.
HetNet	Heterogeneous network.
HAP	High-altitude platform.
HF	High frequency.
ICAO	International Civil Aviation Organization.
IP	Internet protocol.
km/h	Kilometers per hour.
LAP	Low-altitude platforms.
L-DACS	*L*-band digital aeronautical communication system.
LED	Light-emitting diode.
LOS	Line of sight.
LTE	Long-term evolution.
MAC	Media access control.
MANET	Mobile *ad hoc* network.
MCA services	Mobile communication services on aircraft.
MHz	Megahertz.
MIMO	Multiple-input multiple-output.
MTSAT	Multifunctional Transport Satellite.
NASDA	National Space Development Agency.
NextGen	Next Generation Air Transportation.
NET	Network.
NM	Nautical mile.
OFDM	Orthogonal frequency-division multiplexing.
PHY	Physical.
PPM	Pulse-position modulation.
PSR	Primary surveillance radar.
QoE	Quality of experience.
QoS	Quality of service.
RA	Resolution advisorie.
SELCAL	Selective Calling.
SESAR	Single European Sky ATM Research.
SHF	Super HF.
SNR	Signal-to-noise ratio.
SSL	Secure sockets layer.
SSR	Secondary surveillance radar.
STBC	Space-time block coding.
TA	Traffic advisorie.
TCAS	Traffic collision avoidance system.
TDD	Time-division duplex.
TDMA	Time-division multiple access.
TDOA	Time difference of arrival.
TLS	Transport layer security.
TRACON	Terminal radar approach control.
UAT	Universal access transceiver.
UAV	Unmanned aerial vehicles.
UHF	Ultrahigh frequency.
UL	Uplink.
US	United States.
VANET	Vehicular *ad hoc* network.
VDL	VHF data link.
VHF	Very HF.
VoIP	Voice over IP.
WAM	Wide-area multilateration.
WiFi	Wireless fidelity.
WiMAX	Worldwide interoperability for microwave access.

I. INTRODUCTION

Transcontinental travel and transport of goods has become part of the economic and social fabric of the globe. Therefore, the number of domestic and international passenger flights is expected to grow for years to come. For Europe as an example, it is predicted that there will be 14.4 million flights in 2035, which corresponds to a 1.8% average annual growth compared to the flights in 2012 [1]. However, passenger aircraft remains one of the few places where ubiquitous data connectivity cannot be offered at high throughput, low latency, and low cost. A survey by Honeywell [2] revealed that nearly 75% of airline passengers are ready to switch airlines to secure access to a faster and more reliable Internet connection on-board and more than 20% of passengers have already switched their airline for the sake of better in-flight Internet access. Furthermore, in an effort to provide potentially more efficient ATM capabilities, "free flight" [3] has been developed as a new concept that gives pilots the ability to change trajectory during flight, with the aid of GSs and/or ATC. These demands have inspired both the academic and industrial communities to further develop aeronautical

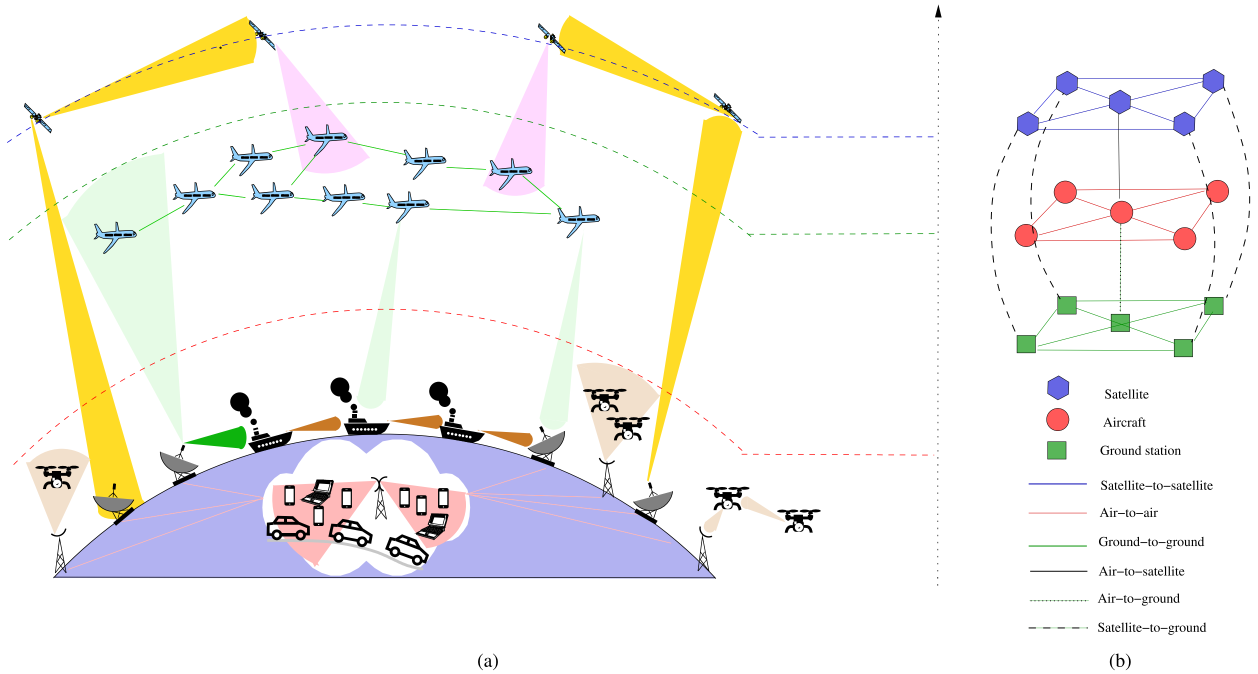


Fig. 1. ***AANET topology and the corresponding logical topology. (a) PHY topology. (b) Logical topology.***

communications. The joint European-American research activities were launched in 2004 for further developing the future communication infrastructure [4], led by the NextGen in the United States and by the SESAR in Europe. However, they mainly focused their attention on improving aeronautical communications for ATM rather than on providing stable Internet access during cross-continental flights. Nonetheless, the ever-increasing interest in providing both Internet access and cellular connectivity in the passenger cabin has led to the emergence of in-flight WiFi based both on satellite connectivity and on the Gogo A2G network. However, they suffer from expensive subscription, limited coverage, limited capacity, and high end-to-end delay. As a complement and/or design alternative, the AANET [5], [6] concept has been conceived as a large-scale multihop wireless network formed by aircraft, which is capable of exchanging information using multihop A2A radio communication links as well as integrating both the satellite networks and the ground networks., as shown in Fig. 1. More explicitly, the middle layer of objects is constituted by the aircraft of an AANET, which are capable of exchanging information with the satellite layer (top layer) and GS layer (bottom layer) via interlayer links. Furthermore, AANETs are also beneficial for automatic node and route discovery as well as for route maintenance as aircraft fly within the communications range of each other, hence allowing data to be automatically routed between aircraft and to or from the GS. The representative benefits of AANET are summarized as follows.

1) *Extended Coverage:* AANETs extend the coverage of A2G networks offshore to oceanic or remote airspace by establishing an *ad hoc* network among aircraft and GSs. The GSs may also communicate with each other as part of an AANET or they may act as a gateway for connecting with the Internet via a fixed line. More specifically, AANETs are capable of substantially extending the coverage range in the oceanic and remote airspace, without any additional infrastructure and without relying on satellites.
2) *Reduced Communication Cost:* Avoiding satellite links directly reduces the airlines' cost of aeronautical communication since the cost of a satellite link is usually significantly higher than that of an A2G link [7].
3) *Reduced Latency:* Another potential benefit of AANET is its reduced latency compared to geostationary satellite-based access; hence, it is capable of supporting more delay-sensitive applications such as interactive voice and video conferencing.

The improvements that AANET offers to civil aviation applications may be much appreciated by the passengers, operators, aircraft manufacturers, and ATCs. More specifically, AANET allows aircraft to upload/download navigation data and passenger service/entertainment data in a wireless live-streaming manner. The congestion of the airspace at peak times will be mitigated by the more punctual scheduling of takeoff/landing. Furthermore, AANET allows direct communication among aircraft for supporting formation flight or for preventing disasters and terrorist attacks. It also grants access to the Internet and facilitates telephone calls above the clouds, as well as maintaining communications with airlines for various purposes, such as engine performance or fuel consumption reports.

A. Motivation

As a new breed of networking, AANET aims to establish an *ad hoc* network among aircraft for their direct communication in high-velocity and high-dynamic scenarios, in order to handle the increasing flow of data generated by aircraft and to provide global coverage. AANETs have become an increasingly important research topic in recent years, and considerable progress has been made in conceiving the network structure [5], [6] and network topology [8]. However, the significant remaining challenges must be overcome before they can be implemented in commercial systems. Airlines are demanding the connectivity offered by AANETs to provide on-board WiFi, while governments need AANETs for improving the operating capacity of the airspace. To motivate researchers both in the academic community and in the industrial community, as well as those who are concerned with the development of aeronautical communication, it is essential to understand the potential applications, requirements, and challenges as well as the existing aeronautical communication systems/techniques. Despite these compelling inspirations, at the time of writing, there is a paucity of detailed comparative surveys of aeronautical communication solutions designed for commercial aircraft taking into account their specific characteristics, scenarios, applications, requirements, and challenges. Hence, we aim to fill this gap by conceiving this survey of AANETs. The objective of this survey is to offer an insight for inquisitive readers into the current status and the future directions of AANETs. We aim for motivating engineers in the aviation industry and researchers in the academic community to contribute to the development of AANETs.

B. Our Contributions

More specifically, we compare the AANETs to the existing family members of wireless *ad hoc* networks by identifying the specific features of AANETs. Following this, we investigate different scenarios of AANETs, including airports as well as populated and unpopulated areas, which result in strict requirements and impose challenges on the design of AANET. Before we scrutinize the remaining challenges, we comprehensively review the field of aeronautical communications in terms of A2G communications, A2A communications, A2S communications, in-cabin communications, and multihop communications. Their capabilities in meeting the requirements as well as in accommodating diverse fundamental and enhanced aeronautical applications are also investigated.

Then, the challenges associated with designing AANETs are analyzed, and the recent research progress in addressing these challenges is also discussed. To facilitate future research in investigating AANETs, we provide a general design framework for AANETs and highlight some key technical issues in designing AANETs as well as present some of our recent experimental results. Moreover, we outline a range of performance metrics in jointly optimizing the AANET design as well as a number of representative multiobjective optimization algorithms. Based on the lessons learned from prior research, we also suggest promising research directions for AANETs, as well as highlight the open issues to be solved for implementing AANETs in practice.

C. Organization

The rest of this paper is organized as follows. The comparison between the family members of wireless *ad hoc* networks is presented in Section II. Section III is devoted to the description of aircraft networking applications, including flight data delivery at airports, ATC, aircraft tracking, formation flight, free flight, and passenger entertainment. The typical aircraft networking scenarios of airports, populated areas, and unpopulated areas will be discussed in Section IV. In order to reliably operate in miscellaneous scenarios and applications, AANETs have to meet specific requirements, which are discussed in Section V. In Section VI, we describe both the existing and emerging aircraft communications systems and discuss their suitability to AANETs. We will also demonstrate that there are still some challenges to be addressed, as discussed in Section VII. In Section VIII, we review the research efforts invested in addressing the open AANET challenges. The relevant design guidelines and the key technologies are illustrated in Section IX. The prospective solutions and open issues of AANETs are discussed in Section X. Finally, our conclusions are offered in Section XI. The organization of this paper is shown at a glance in Fig. 2.

II. COMPARISON OF EXISTING *AD HOC* NETWORKS

The MANET paradigm has been developed for providing direct network connections among wireless devices. During the earliest stage evolution, the nodes were mobile users, later the nodes evolved to vehicles, and then, the nodes evolved to UAVs, and in this treatise, the nodes evolve to airplanes. The acronym MANET constitutes a generalized terminology, which includes *ad hoc* networks mobile users, vehicles, and UAVs as well as airplanes. However, the specific terminologies of VANETs, FANETs, and AANETs refer to the networks constituted by vehicles, UAVs, and airplanes, respectively. In this section, we will compare the existing MANETs, VANETs, and FANETs with the AANETs in terms of their fundamental characteristics.

A. Comparison Between AANETs and MANETs

The MANET concept was conceived in the 1990s to enable nearby users to directly communicate with each other without the need for any central network infrastructure. This is achieved by exploiting the user devices'

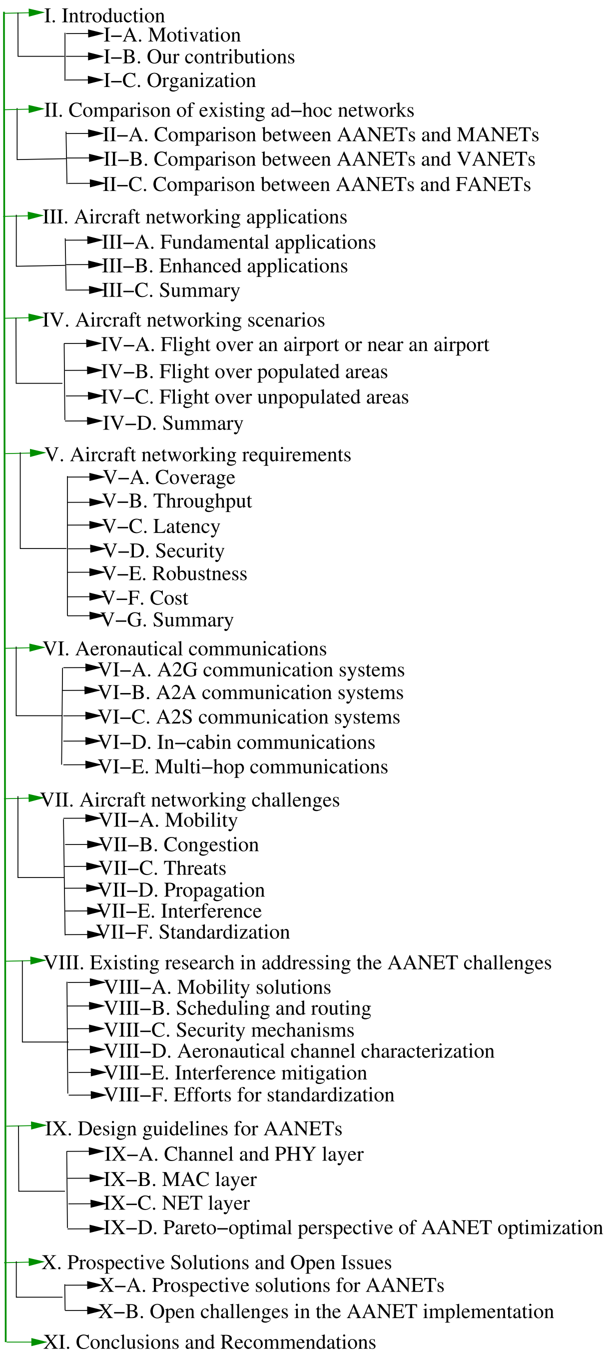


Fig. 2. ***Skeleton structure of this paper.***

wireless interfaces in an *ad hoc* manner, in order to exchange data or relay traffic [9]. Given their high-velocity node mobility, dynamic topology, decentralized architecture, and limited transmission range, legacy Internet routing, and transport protocols do not work properly in MANETs; hence, the recent research efforts have been focused on these areas. More particularly, Abid *et al.* [10] present a survey of the distributed hash table-based routing protocols that are capable of enhancing MANETs while identifying their features, strengths, and weaknesses as well as the corresponding research challenges. With the advent of the future Internet architecture, relying on the information-centric network concept, the Internet is moving from the conventional host-centric design to the content-centric philosophy. A new form of MANETs termed as the information-centric MANET has also emerged. Liu *et al.* [11] interpret the formation of information-centric MANET and define the conceptual model of its content routing. Three types of schemes, namely, proactive, reactive, and opportunistic arrangements, are also described to exemplify the content routing procedure. Apart from routing, surveys on important aspects such as security and neighbor discovery have also been produced by the MANET research community, which shows that the routing information and encryption defeating approaches [12] are the most effective MANET security solutions. Dorri and Kamel [12] have also characterized a range of energy-efficient neighbor discovery protocols [13] in order to emphasize the need for connectivity maintenance and context awareness.

AANETs constitute a new member of the MANETs family since they inherit some of the general mobility features of the nodes, as well as the dynamic nature of the network topology, and the self-organizing traits of the network. However, they also differ quite significantly in a range of specific aspects. In terms of mobility, a mobile device of MANETs typically travels at human walking speed in random directions and exhibits varying node density. By contrast, the aircraft of AANETs typically travel at high speed along planned flight trajectories while exhibiting a much lower node density while en-route over the ocean. Thus, the mobility models for emulating the node behaviors are completely different for MANETs and AANETs. Hence, the random walk model designed for MANETs [14] is not AANETs, whereas the smooth semi-Markov model designed for AANETs is not directly usable for MANETs. In addition, the power consumption is also rather different for MANETs and typically battery-powered nodes of MANETs have to utilize energy-efficient methods in order to extend the network lifetime. On the other hand, aircraft are powered by jet engines, which can provide ample power for communication systems. Hence, the power consumption of AANETs does not impose challenges. Furthermore, radio propagation characteristics are also different. MANETs operate on the ground and they are from Rayleigh fading. By contrast, an LOS path propagation exists for a pair of A2A communicating aircraft. The above-mentioned differences may also result in notable routing and forwarding differences at the network layer. Explicitly, the routing and forwarding methods assist in avoiding congestion by aiming for the maximum throughput per aircraft while maintaining the shortest possible end-to-end delay from one continent to another. This is because both the throughput and the delay constitute key requirements for passengers accessing the Internet. On the other hand, energy-aware routing as well as proactive and reactive routing are favored in MANETs, since they

Table 1 Most Recent Surveys Related With FANET and Their Main Contributions

Year	Paper	Focus/Main Contributions	Object
2011	Bauer and Zitterbart [25]	Protocols that support IP Mobility	Airplanes
2013	Neji *et al* [4]	Development activities from 2004 to 2009, PHY layer and MAC layer for L-DACS	Airplanes
2013	Bekmezci *et al* [26]	Applications, design considerations, communication protocols	UAVs
2015	Saleem *et al* [27]	Cognitive radio technology	UAVs
2016	Gupta *et al* [28]	Routing protocols, handover schemes, energy conservation	UAVs
2016	Zafar and Khan [29]	Societal concerns	UAVs
2016	Hayat *et al* [30]	Applications, network requirements	UAVs
2017	Sharma and Kumar [31]	Taxonomy of multi-UAVs, network simulators and test beds	UAVs
2018	Khuwaja *et al* [32]	Propagation characteristics of UAV channels	UAVs
2018	Cao *et al* [33]	LAPs, HAPs and integrated airborne communication networks	UAVs, airships, balloons
2018	Liu *et al* [34]	Integration of satellite systems, aerial networks, and terrestrial communications	Satellites, UAVs, airships, balloons, ground base station and mobile users
This paper		Scenarios, applications, requirements, challenges, comprehensive survey of existing aeronautical systems	Passenger airplanes

maximize the network lifetime and mitigate the effects of its unpredictable dynamic nature.

B. Comparison Between AANETs and VANETs

AANET relies on *ad hoc* networking, which can disseminate information using multihop communication without a central infrastructure. *Ad hoc* networks have already been developed for ground-based VANET [15], which constitute a subclass of MANET [16], [17]. For example, VANETs have been successfully applied in collision warning [18], in road trains for allowing vehicles to be driven in formation [19], as well as for providing Internet connectivity [20], [21] in vehicles. Although both AANET and VANET are forms of *ad hoc* networking, the transceivers, receivers, and routers in AANET are carried by aircraft. These systems must be designed for exploiting all aircraft assets, in order to connect with satellite and ground networks for the sake of constructing a seamless communications platform across the air, space, and terrestrial domains.

Furthermore, AANETs have many different characteristics compared to conventional VANETs. First of all, the speed of nodes in VANETs is much lower, staying within the range of a few km/h to tens of km/h for the higher speed VANETs [8]. However, the nodes in AANETs, namely, aircraft, fly at velocities of 800 to 1000 km/h. This very high velocity leads to serious Doppler shift and highly dynamic mobility, which results in the frequent setup and breakup of communication links between aircraft. Second, aircraft may fly over a very large-scale range, spanning across oceans, deserts, and continents. In unpopulated areas, such as the North Atlantic, the aircraft density is relatively low, but the aircraft routes are planned and updated twice daily by taking into account both the jet stream and the principal traffic flow, leading to a very sparse but relatively stable network topology. However, the route can be adjusted according to an aircraft's own specific circumstances, in order to reach the destination airport faster or to aim for a particular landing slot. Furthermore, in continental airspace or near airports, aircraft move at random angles to each other, especially in the high-density European airspace [22]. Third, the antenna employed by aircraft have the rigorous requirements of good isolation, high efficiency, and ease of integration with the aircraft [23]. The suitable antenna installation sites on aircraft are typically limited to the wings, tail units, or pertaining control flaps [24]. In addition, the implementation and deployment of communication systems may be overlooked in some research work, but it is of vital significance in aircraft communication systems. The lack of understanding of the economic value, the security mechanisms, and its added value for users may make the deployment of AANET appear risky to manufacturers, airlines, and regulatory organizations. Even once AANETs have been implemented and deployed in aircraft, they also face the challenges of meeting different regulations for aircraft communication and Internet access in different countries. Therefore, further significant challenges are faced by AANET.

C. Comparison Between AANETs and FANETs

A relatively new research area of *ad hoc* networks has gained significance in the wireless research community, namely, FANETs. This is a type of *ad hoc* network that connects UAVs and allows them to autonomously conduct their tasks. No doubt that AANETs and FANETs share some common features in terms of their mobility and dynamic topology. However, UAVs are rather different in terms of their flying speed, flying altitude, trajectory, and geographic coverage. Furthermore, they also differ in terms of their technical specifications, applications, and requirements. This section identifies the contributions of this survey on AANETs beyond some of the most recent surveys of FANETs, accentuating the differences between the two.

The insightful surveys [26]–[32], [34] have covered a wide range of fundamental issues, such as channel modeling [32], radio frequency (RF) aspects [27], communication protocols [26], [28], simulators and testbeds [31], application issues [26], [30], as well as societal concerns [29]. In Table 1, we summarize the most representative survey papers on FANETs from the past five years, which have focused on various subjects of research and challenges. More specifically, Bekmezci *et al.* [26] cover diverse application scenarios and design considerations for the PHY layer as well as communication protocols up to the transport layer of FANETs. Gupta *et al.* [28] focus on the three important issues in UAV communications networks, namely, on existing and new routing protocols conceived for meeting various requirements, such as seamless handovers to allow flawless communication, as well as energy conservation across different communications layers. Zafar and Khan [29] touch not only on the technical aspects of previous surveys but also on the societal concerns in terms of privacy, safety, security, and psychology, plus on the military aspects. Meanwhile, Hayat *et al.* [30] primarily focus on the communication demands of FANETs from two unique perspectives, namely, identifying the qualitative communication demands as well as quantitative communication requirements in the context of four main applications. By contrast, Saleem *et al.* [27] stress the need for and potential applications of CRT designed for UAVs, as well as its integration issues and future challenges. Sharma and Kumar [31] focus on the network architecture and, in particular, on the taxonomy of multi-UAVs, as well as on network simulators/test beds constructed for UAV network formation. Recently, Khuwaja *et al.* [32] provided an extensive survey of the measurement methods of UAV channel modeling and discussed various channel characterization for UAV communications. Cao *et al.* [33] presented an overall view on research efforts in the areas of LAP-based communication networks, HAP-based communication networks, and integrated airborne communication networks. Liu *et al.* [34] comprehensively surveyed the integration of satellite systems, aerial networks, and terrestrial communications, focusing on the aspects of cross-layer operation-aided system design, mobility management, protocol design, performance analysis, and optimization.

Despite some similarities between AANETs and FANETs, however, there are also significant dissimilarities between them. In terms of mobility, AANETs have to cope with a significantly higher velocity than FANETs, since commercial aircraft travel at cruise speeds of 880 to 926 km/h, while most UAVs typically travel at speeds of 30 to 460 km/h [26].[1] Due to this substantial difference in mobility patterns while flying, AANETs require mobility models characterizing high Doppler wireless channel fluctuations as well as more prompt topology changes than FANETs.

Furthermore, because their size is of a completely different scale, their antenna design considerations have to be different. In FANETs, the UAVs are generally not large; hence, the type and structure of the antenna are of grave concern. By contrast, we have to avoid blocking the signal propagation path in AANETs when installing antennas on aircraft. In addition to the antenna and aircraft size, the altitude also makes a difference. For AANETs, the flying altitude is typically 10.68 km, while for FANETs, the maximum flying altitude is generally regulated as 122 m (400 ft) [27]. More specifically, because of the limitations of currently available sensors as well as the wind speed at higher altitudes and the weather conditions, UAVs are constrained in terms of their altitudes. Therefore, the communication range and communication structure of FANETs are different from that of AANETs.

One of the most substantial differences between AANETs and FANETs is their throughput requirement. Because of the massive throughput demand of the "Internet above the clouds," the throughput requirements of AANETs have to satisfy the passengers' needs in the aircraft. The recently developed GoGo@2Ku is capable of delivering 70-Mb/s peak transmission rate for each aircraft and its next-generation version aims for achieving a 200+ Mb/s peak transmission rate [35]. On the FANET side, although the throughput requirements vary between applications, the one that requires the highest throughput is visual tracking and surveillance, as exemplified by a rate of 2 Mb/s for video streaming [30]. The total throughput requirement of the most demanding applications in FANETs is still at least one or even two order(s) of magnitude lower than that of AANETs. This huge difference leads to significant design and implementational differences in their architecture.

In contrast to the previous FANET surveys concentrating on UAVs, there are also two valuable contributions on airplanes, as summarized in Table 1. However, the aeronautical networks they considered were designed for ATM. Explicitly, Bauer and Zitterbart [25] investigated the protocols that can be used to support IP Mobility for aeronautical communications among airplanes. Neji *et al.* [4] gave an overview of aeronautical communication infrastructure development activities spanning from 2004 to 2009 and focused their attention on the L-DACS in terms of its PHY characteristics and MAC characteristics. However, given the more advanced solutions that we have a decade later, the time has come for us to focus our efforts on aeronautical communication designed for commercial airplanes. Specifically, we offer insights into AANETs, covering their networking scenarios, applications, networking requirements, and real-life communication systems designed for commercial aircraft, as well as into the challenges to be addressed.

A birds-eye perspective of AANET, MANET, VANET, and FANET is illustrated in Table 2, where issues, such as the propagation channel, speed, altitude, network scale, power constraint, node density, and security, are considered. Although the MANET has initially been designed both for mobile phones and for vehicles, we have classified vehicles into VANETs, which are specifically developed

[1]Military UAVs can reach the speed of commercial planes or even exceed it, as exemplified by the RQ-4 Global Hark UAV reaching 640 km/h and the X-47B unmanned combat air system reaching Mach 0.9 subsonic speed, i.e., roughly 1100 km/h. However, these UAVs are not designed for *ad hoc* networking and so they are not considered in our discussions.

Table 2 Comparison Between Existing Networks of AANET, MANET, VANET, and FANET

Networks	Objects	Channel	Speed (m/s)	Altitude (m)	Scale (km)	Power	Density	Security
MANET	Mobile phones	Rayleigh	$0 \sim 1.5$	$1 \sim 250$	0.25	Constraint	Dense	Medium
VANET	Vehicles	Rayleigh/ Rician	$4 \sim 36$	$0.5 \sim 5$	1	Non-constraint	City: dense Rural: sparse	Life critical
FANET	UAVs	Rayleigh/ Rician	$8 \sim 128$	Upto 122	80	Constraint	Mission dependent	Medium
AANET	Airplanes	Rician	$245 \sim 257$	$9100 \sim 13000$	740	Non-constraint	Populated area: dense Unpopulated area: sparse	Life critical

for connecting vehicles. AANET distinguishes itself from MANET, VANET, and FANET in terms of its features, such as its flying speed, network coverage, and altitude, which directly result in new propagation characteristics and impose challenges both on the data link layer and network layer design.

III. AIRCRAFT NETWORKING APPLICATIONS

AANETs are capable of supporting various aviation applications and services for their passengers. More specifically, AANETs are capable of enhancing the existing applications of wireless communication in aviation, such as flight data delivery at airports, ATC, aircraft tracking, satisfying the emerging vision of formation flight and free flight, as well as entertainment, as shown in Fig. 3.

A. Fundamental Applications

1) *Flight Data Delivery:* In preparation for an aircraft's next flight, compressed navigation data, and passenger service, as well as entertainment data are typically uploaded/downloaded to/from the aircraft at an airport. Traditionally, this information is stored and transported using a large-capacity PHY disk. However, getting the right disk to the right aircraft at the right time requires significant effort and resources [36], which is expensive. By contrast, AANETs allow the upload/download of flight summary reports, raw flight data, and passenger audio/video files to/from the aircraft, whenever the aircraft is within communication range of an airport's GSs [37]. AANET can also allow those databases to be maintained in real time, while the aircraft is in flight. In this way, time and expense can be saved by uploading/downloading data not only while the aircraft is parked but also while it is landing, takeoff, and even enroute.
2) *Air Traffic Control:* Maintaining safety and high efficiency are the main objectives of a communication system supporting air traffic, as it will be discussed in Section IV. The current system relies on ground-based radar solutions for centralized surveillance, which allows the air traffic service providers or airline operation centers to receive reports sent by aircraft. However, it is expensive to deploy radar systems, which rely on very large antenna structures and require costly regular maintenance [38]. Moreover, radar-based solutions fail to achieve the ATC's expectation of global coverage, since it is typically not possible to deploy radars in unpopulated areas due to the cost and challenge of maintaining them. Furthermore, they are also impractical to implement on a large scale since they require information from all aircraft to be relayed to the central facility. This problem will be exacerbated as the traffic demand increases [38]. As a solution to this, AANETs can be used in both congested regions and in low-density regions. This may be achieved by using self-organization and multihop relaying for the aircraft to exchange their GPS locations, instead of merely relying on GSs [39]. Because of this, AANET is more capable of meeting the requirements of achieving long range, low latency, automated discovery/healing/control, strong security, and robustness. As an extra benefit, AANETs may allow a minimum safety separation of 5 NMs in unpopulated areas, instead of the current safety separation requirement of 50 NMs.
3) *Tracking of Aircraft:* Almost 900 people lost their lives in the aircraft disappearances and aircraft accidents that happened in 2014 [40]. This motivates an AANET-based live-streaming solution for maintaining the connection between aircraft and the rest of the world, especially in unpopulated areas. Moreover, in the event of an emergency or terrorist attack, the ATC may desire to take control of the aircraft and take whatever action is necessary to maintain safety [41], such as engaging the autopilot [42] and locking out any unauthorized access to the aircraft controls. When the aircraft is flying over a populated area, this could be achieved

1 Fundamental applications:
- Flight data delivery
- Air traffic control
- Tracking of aircraft

2 Enhanced applications:
- Formation flight
- Free flight
- In-flight entertainment

Fig. 3. ***Applications of AANET.***

using GSs. However, when the aircraft is flying over an unpopulated area, such as an ocean or desert, the only option today is to use a satellite link. However, the round-trip latency of satellite links can be as long as 250 ms [43], which may be considered unsuitable for the delivery of emergency control signals. Moreover, during disasters and accidents, organizing, coordinating, and commanding an aircraft are significant technical and operational challenges, which require timely collection, processing, and distribution of accurate information from disparate systems and platforms. These issues impose great challenges in the design of a robust solution for tracking aircraft. However, by exploiting direct A2A communication and multihop relays among aircraft, AANET may provide an efficient and robust network that is capable of meeting these challenges with low latency and high reliability.

B. Enhanced Applications

1) *Formation Flight:* As stated by the European Union's 2020 Vision, the carbon dioxide footprint of aviation should decrease by 50% by the year 2050 compared to 2005. To achieve this goal, one of the promising solutions is formation-flight. This approach is inspired by the formation flight of birds, where a 71% increase in the flying range can be observed [44]. In principle, aircraft could also save fuel by taking advantage of formation flight during the enroute flight phase, thus leading to further reduction of CO_2 emissions and costs. A case study of an aircraft design specifically optimized for formation flight was reported in [45], where an average of 54% fuel savings was observed over the most fuel-efficient long-haul state-of-the-art Boeing 787-8 available in 2011. One of the key concerns in formation flight is collision avoidance, which has rigorous requirements in terms of latency, security, and robustness. At the time of writing the Global Navigation Satellite System (GNSS), together with the inertial navigation system (INS), is used for ensuring accurate and safe spacing between aircraft [45], [46]. However, satellite communications tend to be unreliable and of high latency. Motivated by this, the Airbus 2050 vision for "Smarter Skies" [47] suggests that aircraft should be able to communicate with each other for the purpose of collision avoidance, which will enable aircraft to autonomously maintain the most beneficial separation during formation flight. This requires low-latency communication to enable the real-time autonomous reaction of an aircraft to the movement of a neighbor aircraft during turbulence. This *ad hoc* interaircraft communication is one of the long-term applications of AANETs.
2) *Free Flight:* Pilots now have to ask for permission from ATC for any deviation from the original flight path, as required, for example, by poor weather conditions. ATC responds to the pilots' request according to its perception of the air traffic conditions in the vicinity of the aircraft. However, the ATC may not be able to accurately assess the surrounding conditions of the requesting aircraft since it relies on off-site monitoring by a radar system, for example. The recent aircraft crash of AirAsia flight QZ8501 had asked for permission to climb in order to avoid a storm cluster. However, its request was deferred by ATCs due to heavy air traffic, since there were seven other aircraft in the vicinity. If aircraft in this situation were able to form an AANET, then they would be able to adjust their heading, altitude, and speed based on the information shared by the other aircraft in the AANET. Free flight [47] has become a concept recommended by the ICAO for future ATM. Although the concept of free flight was first proposed about two decades ago, it currently has no feasible technical solution when relying on the traditional centralized technologies, which are unavailable in unpopulated areas. However, the free flight may indeed be achieved by exploiting the self-discovering, self-organizing, and self-healing, as well as the distributed control of AANETs, which is capable of providing robust A2A communication at a low latency.
3) *In-Flight Entertainment:* Design studies carried out by airlines and market surveys of in-flight network providers demonstrate the necessity of high-data-rate communications services for airliners, with an obvious trend toward in-flight entertainment, Internet applications, and personal communications [48] regardless of whether the aircraft is in a populated or unpopulated area. However, the provision of a global airborne Internet service is only possible at the time of writing via satellite links, which are costly and suffer from long round trip delays of up to several seconds [49]. This leads to one of the bottlenecks for the future expansion of the aeronautic industry. AANETs would facilitate multihop communications between aircraft and the ground by establishing an *ad hoc* network among aircraft within reliable communications range of each other. In this way, each aircraft will transmit or relay data packets to the next aircraft or GS, potentially offering lower latency, lower cost, and higher throughput than satellite-aided relaying.

Finally, as a speculative but high-impact research topic, it is worth investigating, whether the myriads of planes in the air might be able to enhance the terrestrial coverage as mobile BSs for users on the ground.

C. Summary

Each application may impose particular requirements, as shown in Fig. 4. Explicitly, online flight data uploading/

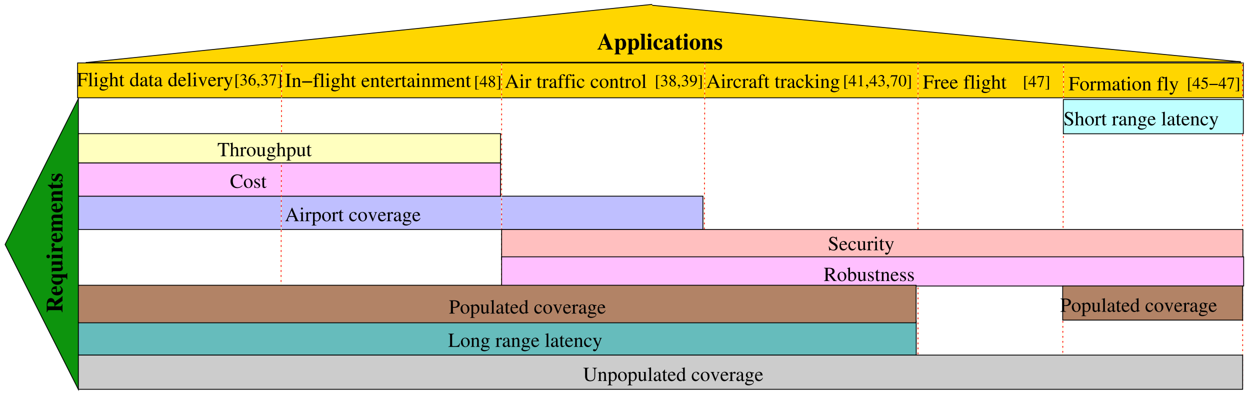


Fig. 4. ***Requirements imposed by the potential applications.***

downloading requires the network to have a global coverage, a high throughput, and acceptable latency in the face of the multihop links invoked for delivering the information. The cost has to be low since there is a requirement for abundant information to be delivered frequently. ATC is safety-related; hence, it has strict requirements in terms of security and robustness. Meanwhile, ATC also requires both global coverage and low latency of the multihop links. Furthermore, the networks have to have the capability of self-discovery/healing/control. Aircraft tracking is generally required in unpopulated airspace, and again, low latency is required. Aircraft heading in the same direction for a long trans-Atlantic journey, for example, may consider formation flight, which will significantly reduce the fuel consumption [45]. Thus, the network should cover both populated and unpopulated areas. The short-range latency must be very low for internal communications within the formation, and the requirements of discovery/healing/control, security as well as robustness are also fundamental to secure formation flying. Free flight may be considered in the airspace over unpopulated areas, which again imposes appropriate requirements on the latency and self discovery/healing/control. Meanwhile, the security and robustness of the network are also crucial for guaranteeing flight safety. Passenger entertainment appeals to a large potential market for the aeronautical industry, but it requires a high throughput at low cost. Furthermore, the passengers tend to expect that the connection is seamless over their entire journey, regardless of whether they are departing from the airport and flying over populated areas or unpopulated areas. The requirements imposed by the potential applications will be detailed in Section V.

IV. AIRCRAFT NETWORKING SCENARIOS

The potential applications supported by AANETs are strictly coupled to different phases of flight, such as landing/takeoff, taxiing, parking, holding pattern, and being en-route. Hence, characterizing AANETs with the aid of a uniform model may not always be possible for different aircraft scenarios since the air traffic density, the mobility pattern, as well as the propagation environment varies significantly both geographically and throughout the day. AANETs are often categorized into three different geographical scenarios, namely, operation in the vicinity of an airport area, a populated area, and an unpopulated area. In Fig. 5, we capture the aircraft pattern of the above-mentioned three representative scenarios of airport, populated area, and unpopulated area, such as London's Heathrow airport, the European airspace, and the North Atlantic airspace, respectively. It can be observed that the aircraft density and mobility patterns are distinctly different. More specifically, in the rest of this section, we will characterize the aircraft networking scenarios of airports, populated areas, and unpopulated areas. The implications of these characterizations will be further discussed as requirements in Section V.

A. Flight Over an Airport or Near an Airport

A high-density area of aircraft is typical in the vicinity of airports, especially near the world's busiest airports. For example, there are about 2544, 1623, and 1378 aircraft takeoffs/landings per day on average at Chicago O'Hare International Airport, Beijing Capital International Airport, and London Heathrow Airport, respectively, as reported by the ACI in August, 2014 [50]. It was also reported that at Heathrow, there is typically a flight takeoff or landing every 45 s [51]. More specifically, the number of landing/takeoff aircraft at Heathrow airport during 12 h of August 26, 2018 is illustrated in Fig. 6. It can be seen in Fig. 6 that there were 335 aircraft takeoff/landing events during the peak hours between 13:00 and 14:00. Furthermore, during our observed period, there were up to 90 aircraft takeoff/landing events in a period of 5 min. The exhausted airspace capacity[2] problems could potentially be overcome with the aid of efficient AANETs, which would enable aircraft to directly communicate with each other for self-organizing takeoff/landing. This not only

[2]The airspace capacity represents the capability of accommodating aircraft within a given airspace in line with current safety separation.

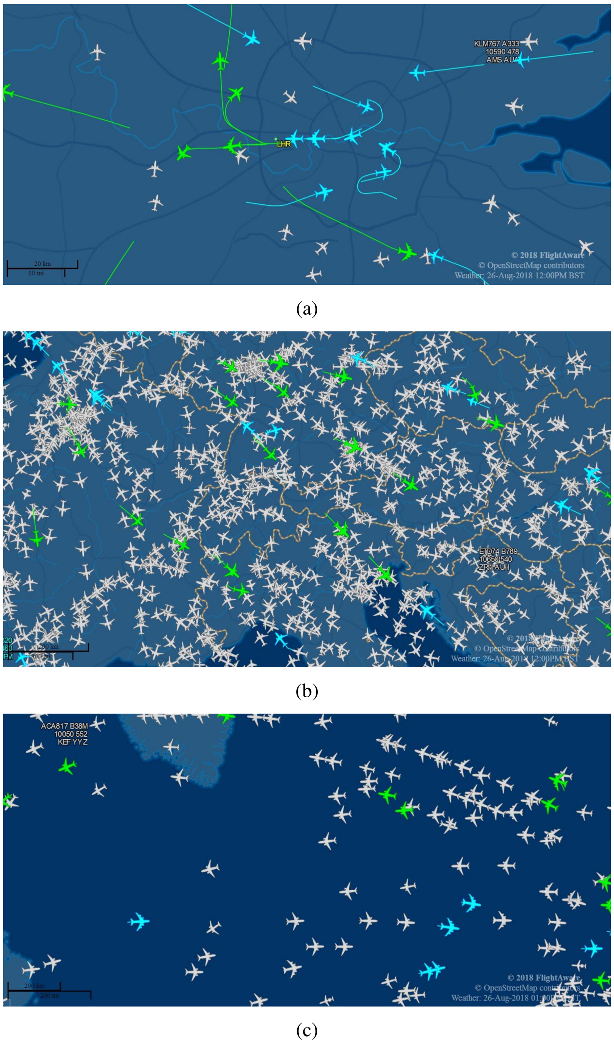


Fig. 5. ***Aircraft mobility patterns. (a) Heathrow airport. (b) European airspace. (c) North Atlantic.***

presents an opportunity for establishing an *ad hoc* network among aircraft but also imposes challenges in terms of both scheduling and interference management. In AANETs, GSs may be deployed at and around the airport, which allow the aircraft to directly communicate with ATC or for messages to be relayed by other aircraft, for the sake of arranging their landing/takeoff, taxiing, and holding patterns [52], [53], as depicted in Fig. 7.

1) *Holding Pattern:* The holding pattern phase is encountered when the aircraft approaches the airport but has no clearance to land yet, which can be seen both from the flight tracks of Fig. 5 and from the flight phases of Fig. 7. Holding pattern procedures are designated to absorb any flight delays that may occur along an airway during airport arrival and on missed approach. This phase results in a Rician-distributed wireless communication channel, as shown in Table 3, since a strong LOS communication path can always be expected due to the proximity to the GS at the airport together with multipath reflections from the ground and the various airport buildings. Frequency-selective fading also takes place in the vicinity of airport due to the delay spread of these multipath reflections. Note that a high Doppler shift may be expected for the LOS path due to the speed of the aircraft [52], leading to time-selective fading. In particular, while performing waiting rounds, it is very likely that the aircraft will fly over the GS, causing a rapid change of the Doppler shifts due to the Doppler rate, which results in rapidly changing Rician fading channels [52].
2) *Landing and Takeoff:* In the takeoff phase, an aircraft becomes airborne and commences climbing under instruction from ATC while increasing its speed. By contrast, in the arrival phase, an aircraft reduces its cruising speed and altitude, descending toward landing. These two phases result in a Rician-distributed wireless communication channel due to the high likelihood of having a strong LOS communication path. As in the holding pattern scenario, frequency-selective fading may be expected due to multipath reflections. Furthermore, a high Doppler shift may be expected because of the speed of the aircraft [52].
3) *Taxiing:* Upon touchdown, the aircraft leaves the runway via one of the available turnoff ramps toward the terminal and vice versa for takeoff. The maximum Doppler and the maximum delay spread have been decreased compared to the landing phase and the takeoff phase. However, the LOS path can be expected to be weaker than the reflections from the ground and from surrounding buildings, which results in a reduction of the Rician K factor, leading to more severe fading of the signal [52].
4) *Parking:* In the parking phase, the aircraft is on the ground and traveling at a slow speed close to the terminal before parking at the terminal. In this phase, the LOS path is often blocked; therefore, the information contained in the received signal has to be reconstructed from the echo paths alone. The fading will be Rayleigh distributed and frequency-selective, depending on the bandwidth of the signal [52].

B. Flight Over Populated Areas

In populated areas, aircraft occupy the international airspace very heterogeneously. Some regions experience dense air traffic, with the aircraft directions being largely uncorrelated, as exemplified by the particular instantiation of the European airspace shown in Fig. 5. Other regions remain only sparsely populated, with aircraft typically flying parallel to each other. Moreover, the number of airborne aircraft in a given region changes significantly throughout the day [22]. In order to ensure the aircraft are adequately separated when en-route, a minimal aircraft separation of 5 NMs is required for continental flights,

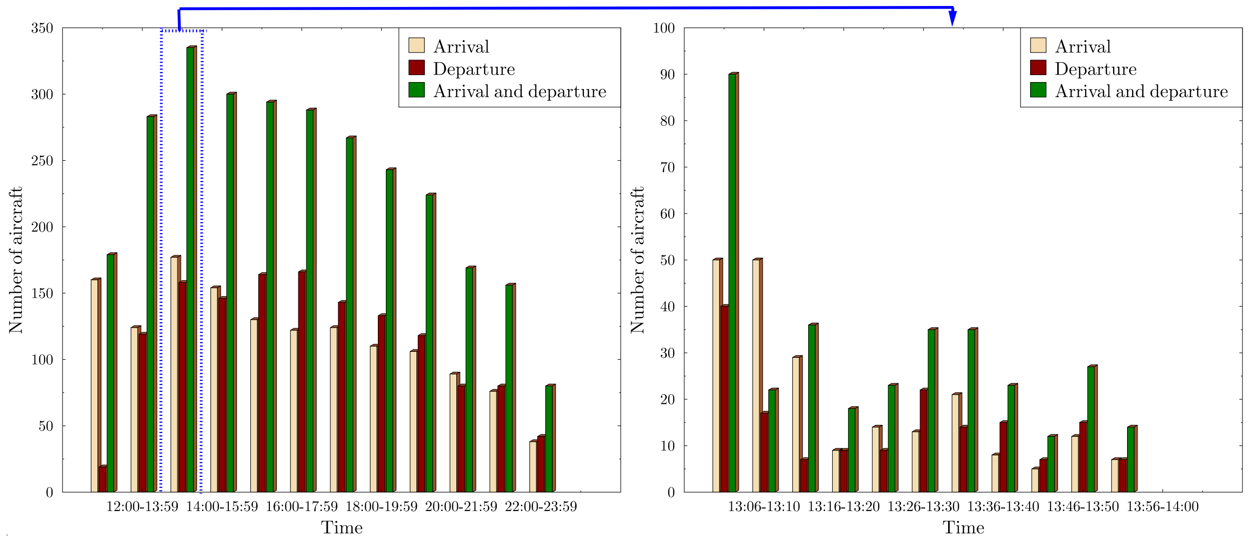


Fig. 6. ***Number of aircraft arrival/departure events at London's Heathrow airport observed on August 26, 2018.***

which is managed by several ground-based surveillance radars. GSs are typically deployed in populated areas, and aircraft fly over GSs when en-route. Thus, satellites may constitute a less attractive solution for relaying information between the GSs and aircraft. However, they may be suitable for relaying information from aircraft to aircraft. In this scenario, the aircraft always engage in A2G communications or may engage in A2A communications when they communicate with each other and act as relays.

1) *A2A:* In the en-route phase, the aircraft is typically navigating a flight-planned route at "optimum" altitudes for its specific weight and engine configuration. This phase will result in rapidly fluctuating frequency-selective fading [52]. The channel-induced dispersion is more severe when compared to terrestrial channels due to the high velocity of the aircraft [54], particularly when two aircraft are flying in opposite directions. In this case, the LOS path is dominant, resulting in Rician-distributed fading.
2) *A2G:* If an aircraft passes over a GS during the flight, the polarity of the associated Doppler shift will change. However, the Doppler shift does not change its polarity abruptly but rather it decreases gradually upon decreasing the projected distance of an aircraft when flying over the GS at altitude. In addition, aircraft turns will also cause a Doppler shift but, in general, lead to lower values of the frequency change [52].

The dynamic nature of aircraft motion will generate different phases associated with diverse channel characteristics. These phases will be characterized by different

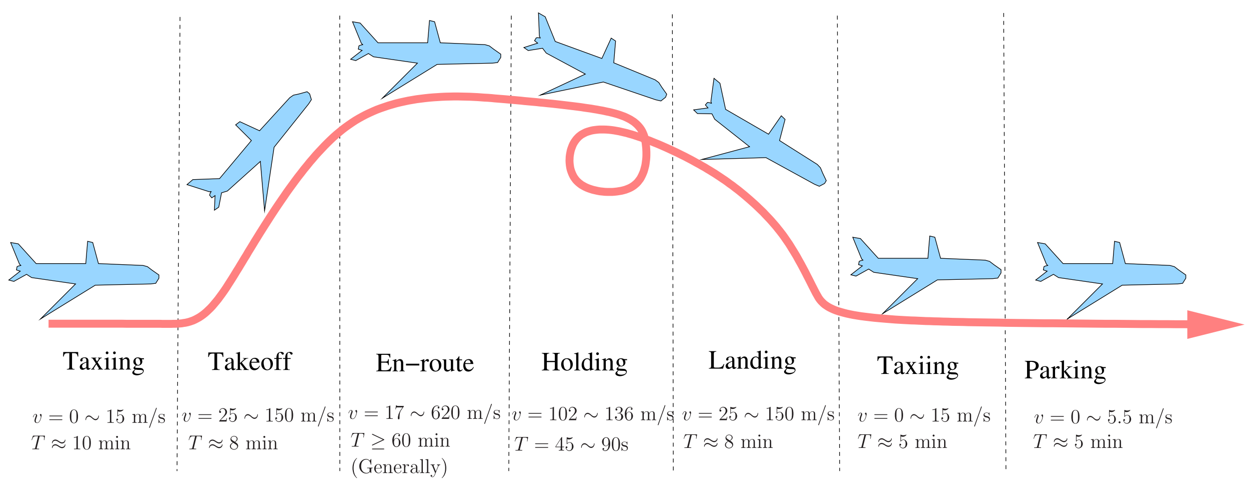


Fig. 7. ***Phases of aircraft flight.***

Table 3 Aeronautical Channel Characteristics for Different Aircraft Flight Phases [52]

Parameters	Parking	Taxiing	Holding	Landing/Takeoff	En-Route (A2A)	En-Route (A2G)
Aircraft velocity (m/s)	$0-5.5$	$0-15$	$102-136$	$25-150$	$245-257$	$245-257$
Maximum delay (s)	7×10^{-6}	0.7×10^{-6}	66×10^{-6}	7×10^{-6}	$66\times10^{-6}-200\times10^{-6}$	$33\times10^{-6}-200\times10^{-6}$
Number of echo path	20	20	20	20	20	20
Rice factor (dB)	/	6.9	$9-20$ (mean 15)	$9-20$ (mean 15)	$2-20$ (mean 15)	$2-20$ (mean 15)
$f_{D_{LOS}}/f_{D_{max}}$	/	0.7	1.0	1.0	1.0	1.0
Lowest angle of beam (°)	0	0	-90	-90	178.25	178.25
Highest angle of beam (°)	360	360	181.75	90	181.75	181.75
Delay power spectrum	Exponential	Exponential	Exponential / Two-ray	Exponential	Two-ray	Two-ray
Slope time[1]	1.0×10^{-6}	1.09×10^{-7}	1.0×10^{-6}	1.0×10^{-6}	/	/

[1] 'Slope time' is the rate of decay in the exponential function that describes the distribution function of delay.

types of fading and Doppler shifts and delays endured by the system. The A2G or A2A channel links will experience time-varying conditions, depending on the specific state of the aircraft journey [53]. Table 3 gives the channel characteristics of the above-mentioned phases of landing, takeoff, taxiing, parking, holding pattern, and en-route. The capacities of the aeronautical channel in different phases are shown in Fig. 8. The achievable capacities of different flight phases are simulated according to the parameters in Table 3. Explicitly, the Rician K-factor is set as 15 for landing/takeoff, en-route (A2A), and en-route (A2G), while it is set to $K = 6.9$ for the taxiing phase. Observe in Fig. 8 that the parking phase has the lowest capacity because it suffers from Rayleigh fading. However, the capacities of the taxiing, landing/takeoff, en-route (A2A), and en-route (A2G) phases are higher than that experienced during parking, as a benefit of LOS propagation leading to Rician fading. More specifically, the capacities of landing/takeoff, en-route (A2A), and en-route (A2G) are almost the same, although they have different scattering characteristics dependent on the presence or absence of LOS. The capacity of the taxiing phase becomes a little lower since its K-factor is lower than that of the landing/takeoff and en-route phases.

The communications range of aircraft is affected by the aircraft altitude, antenna height of the GS, receiver sensitivity, transmitter power, antenna type, coax type, and length as well as the terrain details, especially in the presence of hills, mountains, and so on. Note that the aircraft type will directly affect both the antenna installment and the communications device deployment, which may also affect the communication range. However, the two most crucial factors in determining the communications range are the aircraft altitude and the terrain characteristics. Since VHF radio signals propagate along the LOS path, aircraft that are behind hills or beyond the radio horizon (due to the Earth's curvature) cannot communicate with GSs, even if they experience favorable channel conditions. Considering the Earth's curvature, the geometric distance of horizon (A2G communication range) $d_{\text{A-G}}$ is given by $d_{\text{A-G}} = ((R+h)^2 - R^2)^{1/2}$, where R is the radius of the Earth and h is the altitude of the aircraft. More specifically, given a typical cruising altitude of $h = 10.68$ km, the maximum A2G communication range is approximately $d_{\text{A-G}} \approx$ 200 NM, as shown in Fig. 9. Furthermore, the approximate geometrical area of the communication zone [55] covered by a GS can be defined as the circle having the radius of the geometric distance $d_{\text{A-G}}$ to the horizon, as shown in Fig. 9. Thus, the achievable A2G communication zone is given by $S_{\text{A-G}} = \pi d_{\text{A-G}}^2 = \pi(2Rh + h^2)$. The investigation shows that for lower altitudes, the communication range is predominately limited by the geometric distance of the horizon, while at higher altitudes, it is limited by the signal strength [6].

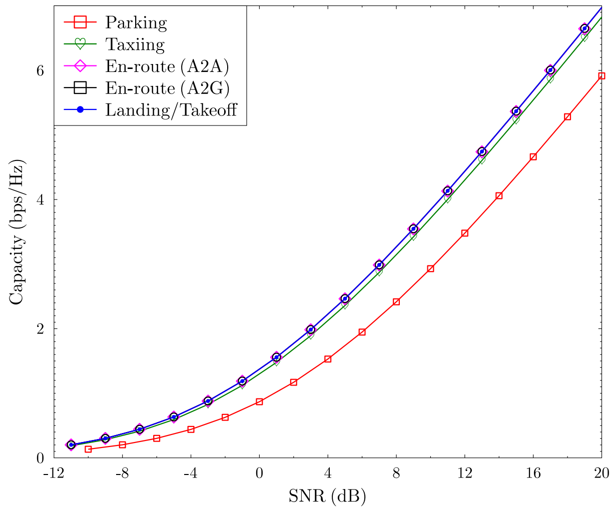


Fig. 8. ***Capacity of aeronautical channel in different flight phases. The Rice factor is set as 15 for landing/takeoff, en-route (A2A), and en-route (A2G), while the Rice factor is set as 6.9 for the taxiing phase.***

C. Flight Over Unpopulated Areas

With the development of a global economy, the number of international flights has increased considerably. Most international flights pass through the North Pacific Ocean or the North Atlantic Ocean, which are areas where it is not possible to build GSs. One of the solutions to this

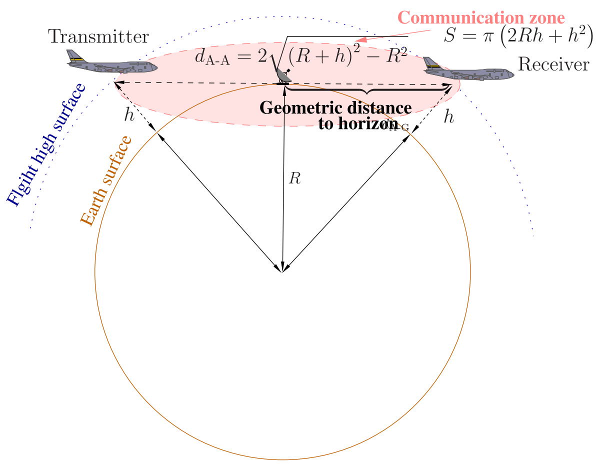


Fig. 9. ***Geometrical area of the LOS communication zone S at flying altitude h.***

problem is to arrange aircraft flying above unpopulated areas to use satellites as relays, albeit this solution is costly and suffers from long round-trip delays [49]. It can be seen in Fig. 5 that a string of aircraft is heading toward the destination continent following a similar route, which may be identified as a pseudolinear mobile entity [8]. The group mobility feature of aircraft flying over unpopulated airspace can be exploited for setting up a large-scale MANETby establishing multihop A2A links among the aircraft [56], where any aircraft can be viewed as a node communicating with its neighbor aircraft for data routing.

The aircraft trajectories above an unpopulated area follow a limited set of predefined routes, and the aircraft density is low when compared to populated airspace [5]. It may be expected that many GSs and radars can be deployed in continental areas. However, these stations and radars are rare in unpopulated areas and they are totally absent in oceanic areas [57]. Thus, in the oceanic areas that are outside of radar range, the safety interval is required to be longer than the above-mentioned 5 NMs. Specifically, they have to be as high as 50 NMs [56] for the sake of avoiding mid-air collisions.

In order to create an AANET, at least the following two criteria must be met [55]. First, there has to be an adequate number of aircraft in the airspace at any given time instant in order for *ad hoc* networking among aircraft to become possible. Second, an aircraft must be within the communication range of at least one other aircraft, in order for a link to be established and for multihop routing to become practical. The maximum geometrical communication range of two aircraft (A2A communication range) at altitude h is defined as $d_{\text{A-A}} = 2d_{\text{A-G}} = 2((R+h)^2 - R^2)^{1/2}$. Specifically, considering a cruising altitude of $h = 10.68$ km, the A2A communication range is limited to a maximum of $d_{\text{A-A}} \approx$ 400 NM. The nominal communication range is likely to be smaller than the maximum communication range $d_{\text{A-A}}$, depending on the transmit power, the specific characteristics of the antenna, the particular modulation used for transmission, and the target BER. Note that different types of aircraft will have different antenna and communications device deployment, which may also affect the attainable communication range.

Here, we provide an example for the probability of having n aircraft in a given A2A communication zone of area $S_{\text{A-A}} = \pi d_{\text{A-A}}^2 = 4\pi(2Rh + h^2)$, which is over the oceanic airspace not covered by the GS service. The probability of the number of aircraft n being within the given region $S_{\text{A-A}}$ may be estimated in [55] by $p(n, S_{\text{A-A}}) = (((\lambda S_{\text{A-A}})^n)/n!)e^{-\lambda S_{\text{A-A}}}$. Given the practical aircraft densities of 900 aircraft and 1800 aircraft over a $S_{\text{A-A}} =$ 9 000 000 km^2 area of the Atlantic ocean at any given time, the average aircraft densities are $\lambda = 1 \times 10^{-5}$ aircraft/km^2 and $\lambda = 2 \times 10^{-5}$ aircraft/km^2, respectively. The estimated number of aircraft at altitudes of $h = 8$ km, $h = 9$ km, $h = 10$ km, and $h = 11$ km within $S_{\text{A-A}} = 9\ 000\ 000$ km^2 are illustrated in Fig. 10. It can be observed in Fig. 10 that the probability of finding at least two or even as many as up to 52 aircraft within $S_{\text{A-A}}$ is close to 100% when we have $h = 9$ km and $\lambda = 2 \times 10^{-5}$ aircraft/km^2. Typically, dozens of aircraft may be expected to be within communication range at any given time. Therefore, the A2G communication zone will be extended by exploiting both multihop as well as direct A2A communication via AANET. More particularly, the communication zone of direct A2A communication will be a circle having a radius of $d_{\text{A-A}}$, which may be capable of achieving global coverage with the aid of multihop *ad hoc* networking among aircraft.

D. Summary

In summary, we have compared the scenarios of flight over airport areas, flight over populated areas,

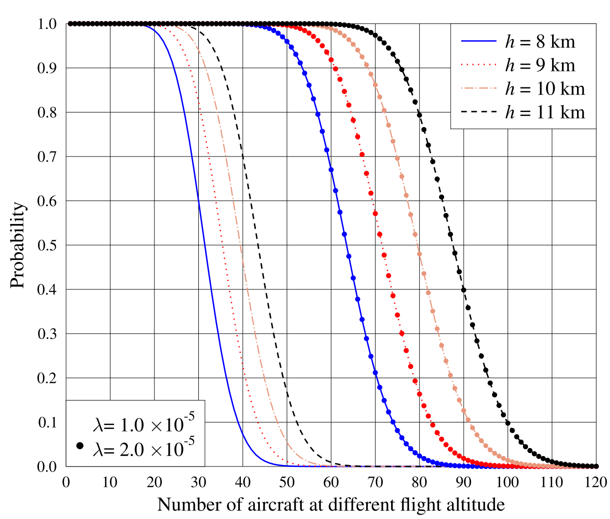


Fig. 10. ***Probability of at least n aircraft appearing in the communication zone S illustrated in Fig. 8.***

and flight over unpopulated areas in terms of the associated flight phases, fading type of the channel propagation, aircraft density, related data links, and potential applications. In Table 4, we summarize some of the salient distinguishing features of the three scenarios discussed in this section. Explicitly, the flight phases of holding, takeoff/landing, taxiing, and parking are always performed at an airport or near an airport. The channel propagation obeys Rician fading for holding, takeoff/landing, and taxiing, while the parking phase suffers from Rayleigh fading, since the LOS path may be blocked by other parked aircraft and airport buildings. Intuitively, the density of aircraft is very high at an airport or near an airport, and the communications are mainly A2G. During the flight phases of holding and takeoff/landing, the ATC messages are the most important ones, while during the phases of taxiing and parking, flight data may be delivered. In the populated continental airspace, the flight phase is en-route and there is typically always LOS propagation for all the A2G, A2A, and A2S data links. The continental air traffic is generally busy associated with a high aircraft density heading in different directions. When the aircraft fly over the continental airspace, offering on-board entertainment is attractive. In the unpopulated airspace, the flight phase is en-route, but the data links are restricted to LOS A2A and A2S propagation due to the absence of ground stations. In the unpopulated airspace, formation flight and free flight may be applicable due to the relative simplicity of their flight lanes in this airspace. Moreover, on-board entertainment is routinely expected during these long periods of flight. In unpopulated areas, aircraft tracking is an important application, which may prevent aircraft disappearance, such as that of the Malaysian Airline plane MH370.

V. AIRCRAFT NETWORKING REQUIREMENTS

As discussed in Sections III and IV, AANET is associated with specific characteristics and applications, which lead to particular requirements, as shown in Fig. 4 and Table 9. This means that the system should treat various types of data differently, depending on the corresponding applications. For example, latency and robustness must be prioritized for safety-critical data. By contrast, in-flight entertainment requires a high throughput in order to service a large number of passengers. In this section, we focus our attention on some representative AANET requirements, which are crucial for designing a feasible and reliable *ad hoc* network for linking up aircraft.

A. Coverage

AANET requires global coverage since aircraft traverse both continents and oceans. However, the achievable AANET coverage is affected by the aircraft mobility pattern, transmission power [58], and propagation environment. Note that the environmental factors also include the diverse effects of the topography, of the PHY obstructions, of the atmosphere, and of the weather. These effects potentially introduce propagation losses and delays, which have to be carefully considered when designing an AANET. Nevertheless, it is still possible to achieve global coverage by falling back upon satellite-aided relaying or upon hybrid satellite/AANET solutions. Furthermore, some additional factors, such as clutter models and obstruction densities, need to be taken into account when considering the coverage in airports. More particularly, the clutter models represent the density of obstructions in the deployment area. An airport surface may have relatively open runways and taxi areas, but congested terminal areas may require the assistance of more fixed infrastructure GSs. A plethora of parameters has to be considered for meeting the coverage requirements of AANETs, such as the GS and aircraft transmit/receive power, antenna gains, feeder losses, and aircraft altitude.

B. Throughput

In general, the throughput requirement depends on that of any other networked aircraft due to the provision of relaying service. Besides the traditional communication systems used for civil aviation, AANETs have to offer comparable or even higher data rates for providing various services, for example, voice + audio, data + security, commercial data, and video. The total bandwidth required depends on the number of passengers that are simultaneously using each service. Therefore, a sufficiently high throughput is required in order to provide services that meet the users' expectations. Vey *et al.* [5] assessed the available throughput of an AANET assuming that the capacity of each relaying node was 1 Mb/s. Their assessment indicated that the achievable throughput of AANETs in the oceanic airspace was better than that attained in the continental airspace, namely, 68.2 kb/s versus 38.3 kb/s, respectively. Wang *et al.* [60] derived the upper bound of the throughput and the closed-form average delay expression of a two-hop aeronautical communication network. Furthermore, Schutz and Schmidt [59] provided the calculation of the required bandwidth in their final report on the RF spectrum requirements for future aeronautical mobile systems. Their prediction was calculated by sharing the overall achievable throughput among 105 aircraft, which is predicted to be the peak instantaneous aircraft count (PIAC) for the airspace sector in the year 2029. Furthermore, a fixed channel rate was selected for the different services in order to calculate the number of channels required. Explicitly, the throughput achieved by each aircraft for the services of voice, data, and video is summarized in Table 5.

Table 5 estimates the throughput required by a single aircraft. However, only two video channels are supported in this analysis, allowing only two passengers to perform video streaming simultaneously. Due to the ever-increasing demand for business/entertainment applications, this is

Table 4 Comparison of the Different Scenarios

Scenarios	Phase	Fading	Density	Data links	Applications
Airport/near airport	Holding	Rician	High	A2G	Air traffic control
	takeoff/Landing	Rician	High	A2G	Air traffic control
	Taxiing	Rician	High	A2G	Upload/Download
	Parking	Rayleigh	High	A2G	Upload/Download
Populated	En-route	Rician	High	A2G/A2A/A2S	Entertainment
Unpopulated	En-route	Rician	Low	A2A/A2S	Formation fly/Free flight/Entertainment/Aircraft tracking

insufficient. In particular, flawless quality video conferencing of a video call requires a throughput of 900 kb/s, given that the video call encodes high-quality voice alone at a throughput of around 40 kb/s [61], [62]. Therefore, much more channels and higher throughput may be required in AANETs.

In airport scenarios, the highest throughput requirements for AANETs emanate from airlines and port authorities, which include communications with ground maintenance crews and airport security. According to a series of studies conducted for the FAA, the company MITER CAASD estimated the potential bandwidth requirements to the year 2020 and beyond for aeronautical communications [63]. The highest total aggregate data capacity requirements for fixed and mobile applications are based on large airports relying on a TRACON ATC facility, which is not collocated with an ATCT. The estimated aggregate data rate requirement of mobile applications is close to 20 Mb/s [63], where the aeronautical operational control data services account for more than half of the 20-Mb/s throughput. The estimated aggregate data rate requirement for these fixed applications is over 52 Mb/s [63]. The combination of video surveillance and sensory information as well as that of the associated TRACON-to-ATCT data communications account for about 80% of the total.

C. Latency

The applications of AANETs having the highest sensitivity to latency are real-time interactive telephony and safety/control applications. For voice telephony, the maximum acceptable latency in a VoIP network is 250 ms [64]. Although a user may tolerate seconds of buffering delay in broadcast video streaming, such a long delay would seriously impair the user's QoE in interactive video conferencing [61], [65]. However, the current latency specification of aircraft VDL is limited to delays below 3.5 s for 95% of the time for data packets [66]. Naturally, this is not suitable for real-time interactive services. Thus, AANETs must be able to offer an order of magnitude improvement in latency while overcoming the challenges associated with multihop scenarios. More specifically, EUROCONTROL/FAA has defined the QoS in form of the distribution of one-way transmission latency designated by the acronym "TT95-1 way" [67] in aeronautical terminology. This terminology becomes explicit in Table 6. For example, observe in the first row of Table 6 that the one-way delay has to be lower than 1.4 s in 99.96% of the scenarios at the airport.

D. Security

An AANET has to guarantee a high level of information security so that the control network can maintain the safety of the flight, while the passenger network can protect the personal data of the passengers. Any networked system must address the following basic security requirements: confidentiality for ensuring the privacy of the end users and for protecting their data from spoofing, authentication for ensuring that only valid users have access to the network's resources, privacy for providing long-term anonymity and for preventing tracking of passengers, traceability and revocation for ensuring that malicious use of on-board units is traced and disabled in a timely manner, and integrity for ensuring that the data sent by the end user is not modified by any malicious element in the network [68].

Thus, in addition to the above-mentioned requirements, an aircraft network has to support additional security for maintaining the separation among various network segments. Any security breach within the control network may result in serious consequences for flight safety. Hence, it is vital to maintain isolation between the control network and the passenger network [68], [69].

Table 7 gives the security requirements of different AANET applications. In the control network, only

Table 5 Throughput for Services of Voice, Data, and Video [59]

Services	DL/UL	Throughput in kBit/s	Fixed channel rate in kBit/s	Required number of channels
Voice	DL	870.41	20	44
	UL	870.41	20	44
Data+Security	DL	809.17	64	13
	UL	3.14	64	1
Commercial Data	DL	197.60	64	4
	UL	197.60	64	4
Video	DL	768.00	384	2
	UL	0	384	0

Table 6 QoS Requirements in Terms of Connectivity[1] and the 95% Percentile of the One-Way Transmission Latency (TT95-1 Way) [67]

	Without automatic execution service[2]		With automatic execution service	
Scenarios	TT95-1 way (s)	Connectivity (%)	TT95-1 way (s)	Connectivity (%)
Airport	1.4	99.96	/	99.99
Terminal Maneuvering Area	1.4	99.96	0.74	99.99
En Route	1.4	99.96	0.74	99.99
Oceanic/Remote/Polar	5.9	99.96	/	99.99
Autonomous Operations Area	1.4	99.96	/	99.99

[1] The lose terminology of 'connectivity' was introduced to indicate that a specific service request was indeed satisfied according to the specification discussed in [67].
[2] The automatic execution service is capable of automatically capturing situations where encounter-specific separation is being used and a non-conformance event occurs with minimal time remaining to solve the conflict.

the authentication requirement is necessitated for the upload/download data-transmission services, while the security has to meet all of the requirements imposed by ATC, aircraft tracking, free flight, and formation flight. In the passenger network, the extreme integrity of data may not be required for passenger entertainment, but all the other requirements have to be met to protect user safety.

E. Robustness

The dynamic nature of the AANET topology has been considered in [5], which may result in interrupted connectivity or even node dropout in the network. In order to maintain connectivity, AANETs must employ specific disruption prevention mechanisms to make them robust. Hence, self-healing relying on distributed and adaptive techniques is desired by AANETs. However, the highly dynamic nature of AANETs results in a potentially intermittent connectivity [71]. To elaborate, the connectivity of the aircraft network is primarily a function of velocity, position, direction, and communication range of the aircraft, which is highly dependent on their mobility. Therefore, a realistic mobility model is required for reflecting the typical movement of the aircraft. The transmitter and receiver of the AANETs have to be robust against both interference and latency, hence requiring sophisticated coding and modulation schemes [4], [72]. The routing of the network has to use redundant multihop paths and be capable of prompt self-healing in order to guarantee sustained connectivity [5]. The aircraft in the system are envisioned to participate as intelligent nodes in a global network of aerial, satellite, and ground systems for ensuring that all information reliably reaches the right place at the right time for both processing and decision making [73].

F. Cost

The cost of manufacturing the AANETs hardware and deploying it within the aircraft will affect how widely it is adopted. Intuitively, an airline will prudently consider the social and economical implications of introducing the function of AANETs. Furthermore, as discussed in Section IV, the first criterion for creating an *ad hoc* network among aircraft is that there has to be an adequate number of compatible aircraft in a given area. Thus, the adoption rate of the AANETs will affect the total value of the network.

Overall, AANETs are required for reliable operation under different channel conditions, diverse network topologies, and various scenarios, both with and without the support of GSs and satellites. It may be impossible to simultaneously satisfy all the requirements and applications. For example, improving the safety may gravely erode the capacity and efficiency of the system. The conflicting requirements will impose challenges, which must be carefully considered for achieving tradeoffs among various criteria.

G. Summary

In this section, we discussed the requirements of the different applications of AANETs shown in Fig. 1. As shown in Fig. 4 and Table 9, the requirements vary depending on the corresponding applications. In order to cater for various applications, the coverage of aeronautical communication has to be global although this is challenging due to

Table 7 Security Requirements of AANETs Applications

	Requirements / Applications	Confidentiality	Authentication	Privacy	Revocation	Integrity
CN	Flight data delivery at airport [36], [37]	√	√			
CN	Air traffic control [38], [39]	√	√	√	√	√
CN	Aircraft tracking [41], [43], [70]	√		√	√	√
CN	Free flight [47]	√	√	√	√	√
CN	Formation fly [45]–[47]	√	√	√	√	√
PN	In-flight entertainment [48]	√	√	√	√	√

CN: Control Network.
PN: Passenger Network.
√: Required.

the high-velocity aircraft mobility, and the associated propagation environment, which introduces propagation losses and delays. Therefore, multihop AANETs are required for meeting the global coverage requirement. Table 5 characterizes the different data throughput requirements of diverse services. Latency is a critical requirement of AANETs because of their safety/control applications but also for real-time interactive telephony. Table 6 summarizes the associated latency requirements [67]. AANETs must provide resilient end-to-end delivery of data, requiring a network relying on self-discovery/healing and reliable control of the communications network. AANETs are also required to decentralize the communication when the associated aircraft are ready to land and leave the network. Another essential requirement for AANETs is security. Table 7 gives the security requirements of different AANET AANET applications in terms of their grade of confidentiality, authentication, privacy, revocation, and integrity. Due to the highly dynamic nature of AANETs, the communication must be robust to delays or link failures. The data routing in AANETs must be intelligent in order to ensure that all information reaches the right place at the right time for both processing and decision requirement identified in this section for AANETs is the manufacturing cost, since this will affect how widely AANETs are adopted. It may be necessary to strike tradeoffs between the cost and other quality criteria such as the throughput.

VI. AERONAUTICAL COMMUNICATIONS

In this section, we will describe a range of existing aircraft communication systems and discuss future techniques [74], [75] considered for mitigating the increasing congestion and for meeting the future demands of sustainable air traffic worldwide [74]. As shown in Fig. 11, the aircraft communication systems and technologies are categorized as A2G, A2A, and A2S. Meanwhile, existing and potential in-cabin communication techniques are also included in this section.

A. A2G Communication Systems

A2G communication is the means by which people and systems on the ground, such as ATC or the aircraft operating agency, communicate with those in the aircraft, which may be outfitted with RF, GPS, Internet, and video capabilities. Most commercial aircraft carry a device known as a transponder, which acts as an identification tool for the aircraft, allowing ATCTs to immediately recognize the identity of each aircraft.

1) *Aircraft Communication Addressing and Reporting System:* ACARS [76] defines a digital data link for transmitting messages between the aircraft and the GSs, which has been in use since 1978. It was developed to reduce the pilot's workload by using computer-based technology for exchanging routine reports, as well as ATC, aeronautical operational control, and airline administrative control information between the aircraft and the GSs, which is now widely used near airports and in populated areas. ACARS permits the secure, authenticated exchange of messages between the aircraft and the ground systems by using the security framework of ICAO and safe public key infrastructure cryptographic algorithms. However, the ACARS system only supports the transmission of short messages between the aircraft and the GSs via HF, VHF, or satellite links [56], which is not sufficient for supporting applications requiring high throughput, low latencies, as well as long-range multihop routing via a self-organizing mesh network.
2) *Selective Calling:* The SELCAL system [77] was introduced in civil aviation as early as 1957, which allows the operator of a GS to alert the aircrew that the GS wishes to communicate with them. This service is robust in the vicinity of airports and in populated areas where the GSs have been well deployed. However, its service is poor in unpopulated areas. The SELCAL system is often employed for reducing the burden on the flight crew due to the intermittent nature of voice communication on long oceanic routes [78]. However, SELCAL is inadequate in latency-sensitive applications. This is because the aircraft receives and decodes the audio signal broadcast by a ground-based radio transmitter, where the transmission consists of a combination of four preselected audio tones whose transmission requires approximately 2 s [77]. The frequency employed is either in the HF or VHF range, where the GS and the aircraft must be operated on the same frequency.
3) *Radar Systems:* Radar systems were originally designed for military applications but are now widely used also in civilian applications for the surveillance of aircraft. There are two types of radar systems used for the detection of aircraft: the so-called PSR and SSR systems [79]. The PSR system measures only the range and the bearing of targets by detecting the radio signals that they reflect. In this way, the PSR is capable of operating totally independently of the target aircraft since no action is required from the aircraft for providing a response. However, the PSR requires enormous amounts of power to be radiated, in order to receive a sufficiently high power from the target, which would be a health hazard if deployed in the vicinity of populated areas. In addition, the PSR requires a significant effort and financial investment to install and maintain due to the mechanical nature of the rotating antenna. By contrast, the SSR systems [79] rely on targets equipped with a radar transponder, which replies to each interrogation signal by transmitting a response containing encoded data. There are three main advantages of SSR. First, since the

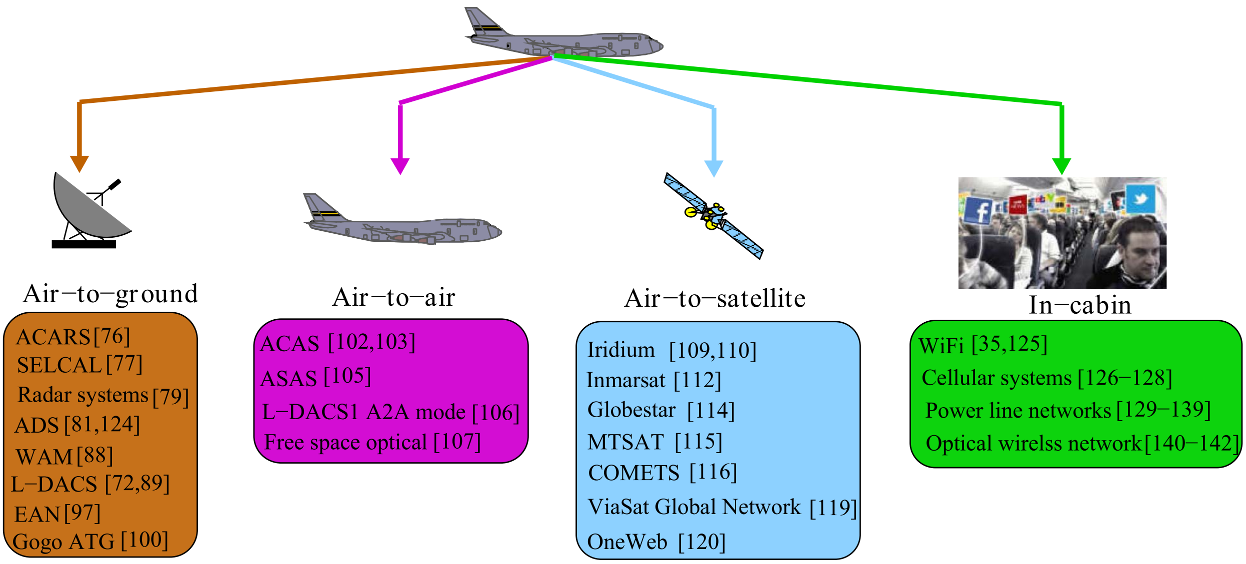


Fig. 11. ***Aeronautical communication systems and techniques.***

reply is transmitted from the aircraft, it is much stronger when received at the GS, hence providing a much higher range than the PSR. Second, the transmission power required by the GS for a given range is substantially reduced, together with the associated cost. Third, since the signals are electronically coded, additional information can be transmitted between the aircraft and the GS, such as the aircraft's position, heading direction, and speed. However, the disadvantage of SSR is that it requires the target aircraft to carry a compatible transponder. Hence, SSR is a so-called "dependent" surveillance system. Passive radar is also a family member of radar systems, which is capable of opportunistically exploiting a variety of transmitters [80], i.e., FM radio, digital audio broadcast, digital video broadcast, GNSSs, and cell-phone BSs for object detection. Explicitly, the TDOA between the signal arriving directly from the transmitter and the signal arriving via reflection from the object is measured for calculating the location, speed, and even the bearing of the objects. Radar systems are capable of providing coverage in airports and in populated areas at a low latency while ensuring robust operation. Because of this, they constitute the main solutions invoked for discovering and monitoring aircraft. However, radar systems cannot deliver data between the GSs and aircraft; hence, they are incapable of data upload/download and of the provision of passenger entertainment.

4) *Automatic Dependent Surveillance:* The ADS system relies on a technique, in which the aircraft uses a data link for automatically providing data derived from onboard navigation and position-fixing systems, including aircraft identification, position, and any additional information as appropriate. This system is automatic because it requires no pilot or controller input for its operation (other than turning the equipment on and logging in to the system). Furthermore, it is referred to as being dependent because it requires compatible airborne equipment, such as an SSR. The original ADS system is known as ADS-C because reports from the aircraft are generated in compliance with a contract set up with the ground system. Furthermore, in order to improve the performance of the ADS system, ADS-B [81] has been designed, which uses a combination of satellites to provide personnel with very specific information about the location and speed of airplanes [82]. As an element of SESAR [83] in Europe and the NextGen [84] in the United States, ADS is being rolled out in support of a variety of applications for oceanic, domestic en-route, and terminal area flight operations, as well as to provide collision avoidance protection when operating in-flight and on the airport ground [39]. A natural limitation of ADS-B is that only the aircraft equipped with the same type of transceiver can exchange their position reports, and there are a variety of different kinds of transceivers, which are designed for diverse aircraft types, regions, locations, and so on. Furthermore, the broadcast aircraft remains unaware, as to whether its report has or has not been received since there is no further broadcast from the receiving aircraft. Moreover, ADS-B may be unsuited for delivering large amounts of data for passenger entertainment since its data link throughput is only about 1 Mb/s [85]. Explicitly, ADS-B replies/broadcasts are

Table 8 Comparison of Different A2G Communications Systems

System	Duplex	Combinations	Modulation / Mode Type	Spectrum	Throughput	Served Domain	Communication Distance	Applications
ACARS [76]	Full-duplex	Telex System	Amplitude Modulation-Minimum Shift Keying (AM-MSK)	3MHz—30MHz(HF), 129.15 MHz—136.90 MHz (VHF)	2400 bps	Airport/ Continent/ Oceanic	Upto 200NM	Data
SELCAL [77]	FDD	/	TDMA	3MHz—30MHz(HF), 129.15 MHz—136.90 MHz (VHF)	Up to 120 kbps	Airport/ Continent/ Oceanic	Upto 200NM	Voice
PSR [79]	/	/	/	2700 MHz—2900 MHz	/	Airport/ Continent	Upto 220NM	Surveillance
SSR [79]	/	/	Mode A, Mode C, Mode S	1030 MHz—1090 MHz	UL 0 bit/s/DL 23 bps	Airport/ Continent	Upto 250NM	Surveillance
ADS-B [81]	TDD	UAT/VDL4	PPM	960 MHz — 1215 MHz (UAT)/117.975 MHz 137 MHz (VDL4)	1 Mbps	Airport/ Continent/ Oceanic	Upto 250NM	Surveillance
WAM [88]	/	/	Mode A/C, Mode S, and Mode S ES (work with SSR)	Depend on the mode employed	/	Airport	Determined by the geometry of the GS	Surveillance
L-DACS1 [90]	FDD	P34, B-AMC & WiMAX	OFDM	960 MHz — 1164 MHz	Upto 1373 kbps (forward link), upto 1038 kbps (reverse link)	Continent	Upto 20 NM	Data
L-DACS2 [91]	TDD	GSM, UAT & AMACS	CPFSK/GMSK	960 MHz — 1164 MHz	273 kbps (forward link/reverse link)	Continent	Upto 200NM	Data
EAN [97]	FDD	LTE	OFDM	2 GHz — 4 GHz	75 Mbps (peak rate)	Continent/ Oceanic	Upto 81NM	Data
GoGo ATG [100]	FDD	CDMA2000	CDMA	4 MHz of spectrum in the 850MHz band	9.8 Mbps per aircraft	Continent	Upto 81NM	Data

encoded by a certain number of pulses with PPM, each pulse being 1 μs long. Because of this, ADS is mainly used by ATC for ATM. However, its security mechanisms are challenged by the lack of entity authentication, message signatures, and message encryption [85], which is requiring more research efforts in such issues. According to the OpenSky report 2016 [86], about 70% of all Mode S transponders in Europe and the United States have already been upgraded with ADS-B capabilities. Moreover, ADS-B systems are to be deployed on most aircraft by 2020 [87].

5) *Wide-Area MultilaterationWAM:* WAM [88] constitutes a surveillance technique that exploits various transmissions broadcast from the aircraft. The WAM relies on a number of relatively simple GSs deployed over the terrain for triangulating an aircraft's position, which is capable of providing accurate localization and robust tracking in its coverage. If a compatible transponder is installed on the aircraft, WAM is capable of tracking various aircraft parameters, such as identification, position, altitude, and so on. This system has the advantage of requiring a much simpler and thus cheaper ground installation than the conventional SSR while not necessarily requiring the installation of expensive aircraft equipment, as required in ADS. Although WAM is capable of tracking and maintaining aircraft for the applications of ATC, it cannot provide data-transmission services, such as passenger entertainment and upload/download. Furthermore, WAM is not suited to latency-sensitive applications, such as formation flight and free flight, since it relies on GSs and does not support A2A communication.

6) *L-Band Digital Aeronautical Communication System:* The L-DACS [72], [89] is one of the most important data links of the FCI. It is designed for mitigating the saturation of the current continental A2G aeronautical communication systems that operate in the VHF band. Furthermore, L-DACS is capable of providing secure and robust data services in populated areas. The ICAO has recommended the further development and evaluation of two L-DACS technology candidates, L-DACS1 [90], and L-DACS2 [91].

   a) *L-DACS1*: It is a combination of the P34 solution (TIA 902 standard) [92], of the B-AMC system [93] and of the WiMAX [94], as illustrated in Table 8. The L-DACS1 system is based on the classic FDD technique, where the GS and the airborne equipment transmit simultaneously using distinct frequency bands [95].

   b) *L-DACS2*: It relies on a combination of the GSM of the UAT and of the AMACS. It uses the GSM PHY layer and the AMACS MAC, as shown in Table 8. The L-DACS2 system is a narrowband single-carrier system utilizing the TDD technique, where both the GS and the airborne equipment transmit using the same carrier frequency during distinct time intervals [95], [96].

Overall, L-DACS1 associated with OFDM is more scalable, more spectrally efficient, and more flexible than L-DACS2, which relies on single-carrier modulation. However, the TDD structure of L-DACS2 is more suitable for asymmetric data traffic, while the FDD of L-DACS1 is more symmetric voice traffic but less suitable for data.

7) *European Aviation Network:* Inmarsat and Deutsche Telekom are powering Europe's aviation connectivity via the EAN [97], which consists of S-band satellite and LTE-based GSs. Explicitly, Inmarsat provides the satellite access service, while Deutsche Telekom build and manage approximately 300 GSs across all the 28 European Union member states based on a 4G-LTE mobile terrestrial network that seamlessly works together with Inmarsat's satellites. Note that the LTE-based GSs built for EAN are different from the "standard" LTE system designed for terrestrial networks since they cater for speeds of up to 1200 km/h at cruising altitudes, requiring a cell diameter of up to 150 km [98]. Furthermore, EAN is capable of providing as high as 50Gbps total network capacity, which allows on-board passengers to enjoy broadband Internet access in the air just as well as on the ground. However, LTE-based A2G communications still suffer from the major challenges imposed by the UL/DL interference, high-Doppler mobility, and hostile channel effects [99].

8) *Gogo ATG Network:* The U.S. provider Gogo has built an ATG network comprising about 200 GSs in the continental area of the United States, Alaska, and Canada [100]. Explicitly, Gogo exploits the existing Airfone ATG phone relay stations and the newly built towers operating in the 850-MHz frequency band in order to provide 3.1-Mb/s data rate for in-flight WiFi for on-board passengers. In order to meet the growing demand for bandwidth, Gogo developed its second-generation ATG technology ATG4, which exploits advanced multiple antenna technology on the aircraft. Explicitly, the aircraft is equipped with four omnidirectional antennas for exchanging data information with the GSs. ATG operates in the 800-MHz frequency band based on the CDMA2000 standard and it is capable of providing up to 9.8-Mb/s data rate [101].

As shown in Table 8, we compare the above-mentioned A2G communication systems in terms of their duplexing mode, modulation type, spectral efficiency, throughput, and served domain as well as their applications.

B. A2A Communication Systems

Aircraft are routinely equipped with GPS for navigation purposes and for A2A communications between pilots. This provides a global time reference that can be exploited for synchronization among network nodes, for example, for scheduling contention-free transmissions [6]. Furthermore, A2A communication is a key technology in future aeronautical communication systems, which aims for separation assurance and collision avoidance, as well as Internet surfing for passenger entertainment. In this section, we will discuss three main technologies used in A2A and a potential technology for future A2A communication, namely, ACAS, ASAS, L-DACS1 A2A mode, and FSO communications.

1) *ACAS:* The ACAS [102], [103] operates independently of any ground-based equipment and ATC, which allows low-latency direct A2A communication among aircraft. It is capable of warning pilots of approaching other aircraft that may present a threat of collision. Specifically, the only commercial version of ACAS-II relies on SSR transponder signals and it will generate an RA to warn the pilot if a risk of collision is established by ACAS-II. The ACAS is a short-range system designed for preventing metal-on-metal collisions by providing secure and robust A2A communication between pilots. There are three types of ACAS [102], namely, ACAS-I that gives TA but does not recommend any maneuvers, ACAS-II that gives TAs and RAs in the vertical direction, and ACAS-III that gives TAs and RAs in the vertical and/or horizontal directions, respectively. More specifically, the implementation of ACAS-II is referred to as the TCAS-II version 7.0 and version 7.1 [104], but ACAS-III has not as yet been rolled out. All three types of ACAS provide only emergency communication between pilots, without supporting data transmission for passenger applications.

2) *ASAS:* The ASAS enables pilots to maintain separation from one or more other aircraft while providing flight information concerning the surrounding traffic [105]. Against the background of the "free flight" concept, ASAS was developed to assist pilots in self-separation, facilitating the flexible use of airspace along user-preferred trajectories, hence allowing direct routing. Similar to the ACAS, ASAS does not support any services for the passengers since it only allows the exchange of flight information among aircraft at a low data rate. Explicitly, airborne surveillance and separation assurance processing equipment is used for processing surveillance reports from one or more sources, which has to assess the target data according to predefined criteria for assisting pilot-controlled self-separation or self-maneuver.

3) *L-DACS1 A2A Mode:* L-DACS1 A2A mode has been designed for the periodic transmission of A2A surveillance data while supporting the transmission of a low volume of nonperiodic A2A messages [106].

The system relies on a self-adaptive slotted TDMA protocol for providing A2A data communication services, using the so-called paired approach, self separation, and ATC surveillance. The maximum net user data rate is up to 273 kb/s [106]. However, the delivery of passenger data is not supported in the current stage of L-DACS, although this will be developed in future versions.

4) *Free-Space Optical:* FSO [107] communication constitutes a promising technique that adopts LDs as transmitters to communicate, for example, between aircraft as well as between aircraft and a satellite at high rates of up to 600 Mb/s for MANET applications [108]. Since FSO signals are very directional and limited to a small diameter, it is virtually impossible to intercept FSO signals from a nondesired destination. This feature can meet the very high-security requirements of aeronautical communications. Establishing their applicability to A2G communications requires further studies due to eye-safety concerns. The directional and license-free features of FSO are appealing in aeronautical communication since the conventional RF communication is fundamentally band-limited. However, FSO communications are vulnerable to mobility because LOS alignment must be maintained for high-integrity communication. In order to solve the associated problem of pointing and tracking accuracy, a feasible solution is to rely on the built-in GPS system of the aircraft, along with the FSO system's low transmission latency, which can also assist in the formation of light. Furthermore, since there are no obstacles in the stratospheres, the main disadvantage of FSO links in terms of requiring a LOS channel becomes less of a problem. Thus, the FSO communication links between aircraft have a promising potential in terms of constructing an AANET for aircraft tracking and collision avoidance. Finally, since FSO and RF links exhibit complementary strengths and weaknesses, a hybrid FSO/RF link offers great promise in future aircraft communications.

C. A2S Communication Systems

Satellite systems are especially important for enabling communications to aircraft in oceanic and other unpopulated areas since they are capable of providing global coverage, as well as global discovery and control for other communication systems. A2S communication also complements A2G communication where appropriate [72], for example, for locating the position of aircraft. However, apart from having a high cost, aeronautical communication relying on satellites suffers from very long end-to-end propagation delays of approximately 250 ms [43], which prevent its use in latency-sensitive applications, such as formation flight. In addition, the achievable throughput is relatively low in the operational satellite systems, making them incapable of meeting the requirements of high-throughput applications, such as online video entertainment via Internet access. In the following discussions, we will briefly consider six existing and emerging satellite systems.

1) *Iridium:* The Iridium network [109] consists of 66 active satellites used for worldwide voice and data communication from hand-held satellite phones to other transceiver units. Although the Iridium system was primarily designed for supporting personal communications, aeronautical terminals having one to eight channels have been developed for the Iridium system by AlliedSignal Aerospace, which are also used for military transport aircraft [110]. As an improved version, Iridium NEXT [111] began to launch in 2015, maintaining the existing Iridium constellation architecture of 66 cross-linked low-earth orbit satellites covering 100% of the globe. It dramatically enhances Iridium's ability to meet the rapidly expanding demand for truly global mobile communications on land, at sea, and in the skies.

2) *Inmarsat:* Inmarsat [112] is a British satellite telecommunications company, offering global mobile services. It provides telephone and data services for users worldwide, via portable or mobile terminals, which communicate with GS through eleven geostationary telecommunications satellites. Inmarsat provides voice/fax/data services for aircraft, employing three levels of terminals: Aero-L (low gain antenna) primarily for packet data including ACARS and ADS, Aero-H (high gain antenna) for medium-quality voice and fax/data at up to 9600 b/s, and Aero-I (intermediate gain antenna) for low-quality voice and fax/data at up to 2400 b/s. In order to enhance the capacity of the Inmarsat system, Inmarsat signed a contract with Boeing to build a constellation of three Inmarsat-5 satellites, as part of a $1.2 billion worldwide wireless broadband network referred to as Inmarsat Global Xpress [113]. The satellites operate in the Ka-band in the range of 20–30 GHz. Each Inmarsat-5 carries a payload of 89 small Ka-band beams, with the objective that a global Ka-band spot coverage can be offered with the aid of all three Inmarsat-5 satellites [113]. There are plans to offer high-speed in-flight broadband on airliners through Inmarsat Global Xpress [113].

3) *GlobeStar:* The GlobeStar system [114] is the world's largest provider of mobile satellite voice and data services. The GlobeStar system consists of 52 satellites, of which 48 satellites provide full commercial service for users, while the other four satellites are in-orbit as spares, ready to be activated when needed. GlobeStar uses a version of classic CDMA technology based on the Pan-American IS-95 CDMA standard, which has made GlobeStar well known

for its crystal clear, "land-line quality" voice service to commercial and recreational users in more than 120 countries around the world. In 2013, GlobeStar successfully completed launching its constellation of second-generation satellites, which support the company's current lineup of voice, as well as duplex and simplex data products and services.

4) *Multifunctional Transport Satellite:* The MTSAT system [115] relies on a series of weather and aviation-control satellites. They are geostationary satellites owned and operated by the Japanese Ministry of Land, Infrastructure, Transport, and Tourism and the Japan Meteorological Agency. Operating in L-band, the MTSAT system provides both communications and navigational services for aircraft and gathers weather data for users throughout the entire Asia-Pacific region. The MTSAT satellite-based augmentation system improves the reliability and accuracy of GPS via MTSAT for aircraft utilizing the GPS position information for their navigation. Unlike the conventional navigational means such as VHF omnidirectional range or distance measuring equipment, it is able to cover a wide range of oceanic and ground areas making it possible to set up flexible flight routes.
5) *Communications and Broadcasting Engineering Test Satellites:* As a collaboration between the CRL of the Ministry of Posts and Telecommunications and the NASDA in Japan, the COMETS [116] system was developed for future communications and broadcasting. It relies on a two-ton geostationary three-axis stabilized satellite. Particularly, it carries three payloads: advanced mobile communications equipment developed by CRL for the Ka-band (31/21 GHz) and the millimeter-waveband (47/44 GHz), 21-GHz band advanced satellite broadcasting equipment developed by CRL and NASDA, and interorbit communication equipment developed by NASDA [117]. The broadcasting experiments conducted for HDTV [118] showed that it was capable of providing a transmission rate of up to 140 Mb/s.
6) *ViaSat Global Network:* ViaSat's airborne satellite communications services offer worldwide access and a range of service levels, providing connectivity and performance options tailored to meet a variety of needs, including office-in the-sky, real-time broadcasting HDTV, communications on-the-move, and ATC. The data rate is expected to range from 512 kb/s to 10 Mb/s [119]. The network's performance is optimized for reliable and secure two-way mobile broadband communications. Therefore, airborne operators have the capability of sending full-motion video, making secure phone calls, conducting video conferences, accessing classified networks, and even to perform mission-critical communications in flight.
7) *OneWeb Satellite Constellation:* The OneWeb satellite constellation [120] was started by telecommunications entrepreneur Greg Wyler with the support of Google. It comprises approximately 648 satellites. The OneWeb satellite constellation is aiming for providing global Internet broadband access for ground users, but it can also be exploited for providing global Internet access for airborne users via A2S links. The OneWeb satellites operate at approximately 1200-km altitude [121], and the frequency spectrum used for providing broadband access service is the Ku-band [122] spanning from 11.7 to 12.7 GHz (DL transmission) and from 14 to 14.5 GHz (UL transmission). Each satellite is capable of supporting 6-Gb/s throughput, while the user is capable of accessing the Internet at 50-Mb/s rate using a phased array-based antenna measuring approximately 36 by 16 cm [123]. While the Ku-band suffers from rain-induced attenuation proportional to the amount of rainfall, this problem may be solved by appropriate link budget design and power allocation for the satellite network.

D. In-Cabin Communications

Although aircraft constitute the end-points of AANETs, passengers on-board the aircraft desire access to the provided throughput. Thus, the existing and potential techniques used for in-cabin communications will be elaborated on as potential extensions.

1) *WiFi:* The popular WiFi system is a local area wireless networking technology, which allows an electronic device to exchange data or to connect to the Internet using the 2.4-GHz UHF band and the 5-GHz SHF radio waves, finding widespread employment in wireless Internet access. This technology can be exploited for the low-cost wireless uploading/downloading of flight information at a high throughput at airports. Furthermore, in response to the passengers' demand, in-flight WiFi is now accessible on about 40% of U.S. flights and on international long-haul flights via companies such as American Airline, Lufthansa, Emirates, and Qatar Airways. Since high-speed data communications are both desirable and important to society, enhanced WiFi techniques are being developed by upgrading the WiFi capacity with the aid of using hybrid technology, such as GoGo's hybrid ground to orbit technology [125]. The recently developed GoGo@2Ku is capable of providing 70-Mb/s peak transmission rate for each aircraft, and its next-generation version aims for achieving a 200+ Mb/s peak transmission rate [35]. However, the service is expensive, 1-h pass plan is \$7.00 or monthly airline plan is \$49.95 at the time of writing.
2) *Cellular Systems:* There is an increasing interest for the passengers to be able to use their smartphones

and laptops on aircraft. More and more firms aim for satisfying the public's urge of mobile communication and surfing the web above the clouds. The United States and Europe are leading the development of wireless communications onboard of aircraft. For example, AeroMobile [126] enables Virgin Atlantic passengers to use their mobile phones during flights over the U.K. airspace, while OnAir [127] enables airline passengers to use their personal mobile devices for calls, text messaging, emails, and Internet browsing. In addition, passengers are offered the opportunity to use their mobile phones onboard via the MCA services [128] in Europe. More specifically, mobile phones may connect to a miniature cellular network installed inside the aircraft. The voice and data traffic are then transmitted to a satellite, which route the traffic to a GS for connecting to the conventional telephone network or to the Internet. However, the reliance on satellites results in a low throughput and a high latency. Furthermore, the MCA services are only allowed for use at altitudes above 3000 m in the European airspace, in order to interference with the terrestrial cellular networks.

3) *Power Line Networks:* Power line networks already exist throughout most aircraft. Thus, Jones [129] proposed to transmit mobile multimedia signals and to offer Internet access over the aircraft power lines by plugging in devices, in order to reduce both the installation costs and the "tetherless" challenges. The transfer function between the input and output ports on a power line of a transport aircraft was modeled for the sake of optimizing the communication parameters. In [130], preliminary theoretical results were presented for a common-mode configuration, whereas in [131], the emphasis was on the electromagnetic compatibility aspects, such as reducing the effects of coupling between wires within the bundle. Degardin *et al.* [132] modeled the channel propagation and investigated the achievable performance under the tree-shaped architecture of a power line network in an aircraft, and they extended the common-mode preliminary results in [130]. They also estimated the expected throughput of different links [133]. Furthermore, field-programmable gate array-based modems were designed, and the performance of the links was investigated by Degardin *et al.* [134], who showed that the BER does not exceed 2×10^{-4} at a bit rate below 91 Mb/s.

4) *Optical Wireless Networks:* Optical wireless networking offers the potential of exploiting a relatively untapped region of the electromagnetic spectrum for communication by exploiting LEDs for information transmission [135]. Optical wireless networking has the advantage of being free from regulation, being untapped, having low-cost front ends, and of delivering high data rates. This approach was proposed for intracabin communication in [136]. The wireless path loss distribution within an aircraft cabin was obtained by performing Monte Carlo ray tracing for the infrared range. Furthermore, the throughput and cell coverage of asymmetrically clipped optical OFDM-based and direct-current offset optical OFDM-based cellular optical wireless networks were compared, as shown in [137]. Zhang *et al.* [138] proposed a Fiber-wireless (Fi-Wi) network for in-cabin communication by considering the tunnel-shape of the cabin, while Krichene *et al.* [139] proposed to exploit the deployment of LEDs in the cabin for designing an in-cabin network architecture. These investigations demonstrated that having an optical wireless network in the cabin is feasible for providing high-data-rate in-flight entertainment services.

E. Multihop Communications

At the time of writing, there is an increasing demand for in-flight Wi-Fi connectivity to the Internet, but the existing solutions do not provide value for money. The Institute of Communications and Navigation of the German Aerospace Center (DLR) conceived the concept of networking in the sky for civilian aeronautical communications [140], which enables the aircraft to communicate with GSs via multihop transmission. As studied by Mahmoud *et al.* [141], even when only a minority of aircraft are directly connected with GSs, the system is capable of connecting most of the remaining aircraft within three hops. Explicitly, given the communication range of 150 km for the continental airspace and 300 km for the oceanic airspace, even if 29.9% of aircraft and 41.7% of aircraft were connected via a single hop, links of up to three hops are able to connect the remaining 70.1% and 58.3% of aircraft flying within the continental airspace and oceanic airspace, respectively.

As an essential solution for providing additional coverage and/or enhancing the capacity of the aircraft network, multihop links are indispensable for providing Internet access to on-board passengers. Another example of multihop networking is illustrated in Fig. 12, where WiMAX operated in the multihop scenario has been invoked for providing broadband access to networks on the ground for on-board passengers [142]. Explicitly, the commercial aircraft is equipped with a WiMAX router, which is capable of communicating with a land-based WiMAX network station. The on-board passengers access the Internet with the aid of the WiMAX router deployed in the aircraft.

VII. AIRCRAFT NETWORKING CHALLENGES

Due to the passengers' desire of establishing an "Internet above the clouds" and driven by handling the continuously increasing air traffic [39], [48], both airlines and aeronautical organizations are motivated to develop and establish broadband aeronautical communications among in-flight

Table 9 Relationships of Aeronautical Communication Applications, Requirements, and Aeronautical Communication Systems/Techniques

	Applications \ Requirements \ Systems/Techniques	Airport coverage	Populated coverage	Unpopulated coverage	Throughput	Short range latency[1]	Long range latency[2]	Security	Robustness	Low cost
	In-fliht entertainment [48]	√	√	√	√	–	√	–	–	√
	Free flight [47]	–	–	√	–	–	√	√	√	–
	Formation fly [45]–[47]	–	√	√	–	√	–	√	√	–
	Aircraft tracking [41], [43], [70]	–	√	√	–	–	√	√	√	–
	Air traffic control [38], [39]	√	√	√	–	–	√	√	√	–
	Flight data delivery [36], [37]	√	√	√	√	–	√	–	–	√
A2X	AANET [5], [6]	∼	∼	∼	∼	∼	∼	∼	∼	∼
A2G	ACARS [76]	↑	↑	↓	↓	∼	/	↑	↓	↓
	SELCAL [77]	↑	↑	↓	↓	↓	↓	↓	↓	∼
	Radar Systems [79]	↑	∼	↓	/	↑	/	/	↑	↓
	ADS [81], [124]	↑	↑	∼	↓	∼	↓	∼	↓	↓
	WAM [88]	↑	↑	↓	↓	∼	/	∼	↓	↓
	L-DACS [72], [89]	↓	↑	↓	↓	∼	↓	↑	↓	↓
	EAN [97]	↓	↑	↓	↓	∼	↓	∼	↓	↓
	Gogo ATG [100]	↓	↑	↓	↓	∼	↓	∼	↓	↓
A2A	ACAS [102], [103]	↑	↑	↓	↓	∼	↓	↑	↓	↓
	ASAS [105]	↑	↑	↓	↓	∼	/	↑	↓	↓
	L-DACS1 A2A mode [106]	/	∼	↓	↓	∼	↓	↑	↓	↓
	Free space optical [107]	∼	∼	∼	↑	∼	/	↑	↓	↓
A2S	Satellite systems [109], [111], [112], [114]–[116], [119]	↑	↑	↑	↓	↓	∼	∼	↑	↓

√ A crucial requirement.
– Not a crucial requirement.
↑ Achieves the requirement to a greater degree than AANET.
∼ Achieves the requirement to the same degree as AANET.
↓ Achieves the requirement to a less degree than AANET.
/ Not applicable.
'1' Short range latency refers to the latency of single hop links.
'2' Long range latency refers to the latency of multiple-hop links.

aircraft. Extensive efforts have been dedicated to building a set of protocols meeting the demanding requirements and applications of future aircraft communications. Different applications of aircraft networks have different requirements, as shown in Table 9. Note that the extensional techniques for in-cabin communication are not included in Table 9. However, all the existing aeronautical communication systems can only meet part of the requirements of each application. For example, passenger entertainment requires the network to cover unpopulated areas at a low cost. However, none of the existing aeronautical communication systems are able to achieve these requirements at the same time, as also seen in the lower part of Table 9. By contrast, AANETs are capable of fulfilling all the requirements and support various applications, including those of the emerging aircraft applications, such as free flight and formation flying. However, numerous challenging open issues have to be addressed in AANETs, as shown in Fig. 13.

Particularly, meeting the requirement of global coverage is highly dependent on the frequency band used, the transmit power and network topology management, which will impose challenges in terms of mobility modeling, propagation characterization, and interference management in AANETs. The throughput of AANETs is directly affected by the mobility management, interference mitigation, propagation characteristics, and network congestion control. AANETs should accurately model the aircraft mobility for managing routing, for providing connectivity, and for avoiding congestion. As illustrated in Fig. 13, network discovery/healing is also challenging in AANETs, due to congestion and mobility, resulting in some nodes disappearing from a local network and joining another *ad hoc* network. The security requirements are very strict for AANETs since commercial aircraft constitute safety-critical systems. Although the highly dynamic nature of AANETs imposes challenges in term of robustness, AANETs must be

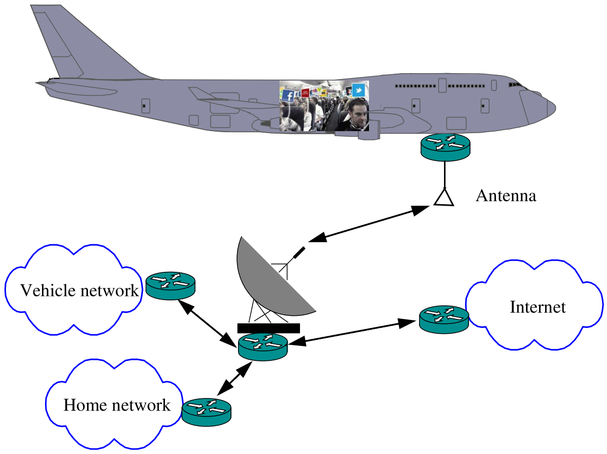


Fig. 12. ***Multihop aeronautical communication via WiMAX.***

highly reliable and robust, in order to protect the safety of hundreds of passengers. Thus, AANETs will face great challenges in terms of security threats and robustness. AANETs are a relatively low-cost solution of exchanging information via an *ad hoc* network established among aircraft, which is mainly dependent on the communication protocol design and on software development, without dependence on large-scale infrastructure deployments. However, global standardization is required to ensure global interoperability, but this must also be harmonized with the country-by-country standards and their own interests. In the following discussion, we elaborate on the challenges imposed by the requirements of aeronautical applications, which must be overcome before AANETs can be considered for practical deployment.

A. Mobility

There is a strong need for providing connectivity for passengers in aircraft so that they can continuously communicate with other devices attached to the Internet, at any time and anywhere. However, the connectivity of the network may be frequently interrupted due to the high velocity of aircraft [25] and occasionally interrupted by weather. This is also an issue for FANETs due to their time-variant scenarios governed by their high mobility. Hence, CR technologies-based UAVs suffer from the fluctuation of link quality and link outages [27]. Moreover, due to the 3-D terrain changes, UAVs have to cope with highly dynamic wireless channel fluctuations as well as topology changes [30]. Hence, the network protocols of FANETs and AANETs have to be more flexible than those of VANETs [30]. Therefore, the investigation of the mobility characteristics of aircraft is a critical issue for designing and evaluating AANETs so that they can provide robust solutions for connectivity at high velocity. Furthermore, other challenges include the tradeoff between the mobility model's accuracy as well as its simplicity for analysis [143], and those associated with a high degree of mobility. The inevitable delay problems due to routing over large geographical distances [25] and the connectivity problems due to the frequent setup and breakup of communication links among aircraft require extremely robust solutions to support high mobility.

B. Congestion

Since AANETs are intended for providing Internet access, hence requiring practically all multihop traffic to flow through the GSs, gateway congestion may be caused at or among the aircraft near these GSs. Liu *et al.* [144]–[146] investigated the impact of gateway placement on the integrated 5G-satellite networks reliability and latency. Similar investigations also have to be applied to aircraft networking for optimizing the gateway selection and/or placement. Wang *et al.* [60] demonstrated that the two-hop model of aeronautical communication networks was capable of achieving the best throughput without long delays. Moreover, by efficiently allocating flows, the traffic may be balanced among the gateways to avoid congestion. Furthermore, this problem is strongly coupled with the routing of packets in the network since the path between an aircraft and a gateway determines the service that the gateway can provide to the aircraft. In addition, if the wireless channel is shared by all nodes in a wireless network, the transmission of one node may interfere with others, which results in congestion of the network [147]. Therefore, the processes of Internet gateway allocation, routing, and scheduling while minimizing the average packet delay in the network have to be jointly optimized, which is a challenging nonconvex optimization problem.

C. Threats

It is extremely critical to secure AANETs from every conceivable threat since any threat may result in aviation accidents and incidents involving the lives of hundreds of passengers. Therefore, the precautionary measures should be thoughtful and proactive. Generally, the security threats to aircraft networks may be categorized into internal and external ones. Internal security threats originate from the in-cabin passenger network, where a malicious user may attempt to gain access to the control network and cause service impairments and/or attempt to take control of the flight. On the other hand, the external security threat is caused by the security vulnerabilities of the communication links [69].

D. Propagation

In the future, the available radio spectrum will become scarcer. However, the signal transmissions in AANETs take place over A2A, A2G, and A2S across airports, populated, and unpopulated areas, each having different bandwidth requirements. The different environments encountered during the flight of an aircraft may lead to different propagation scenarios. As shown in Fig. 14, an AANET may rely

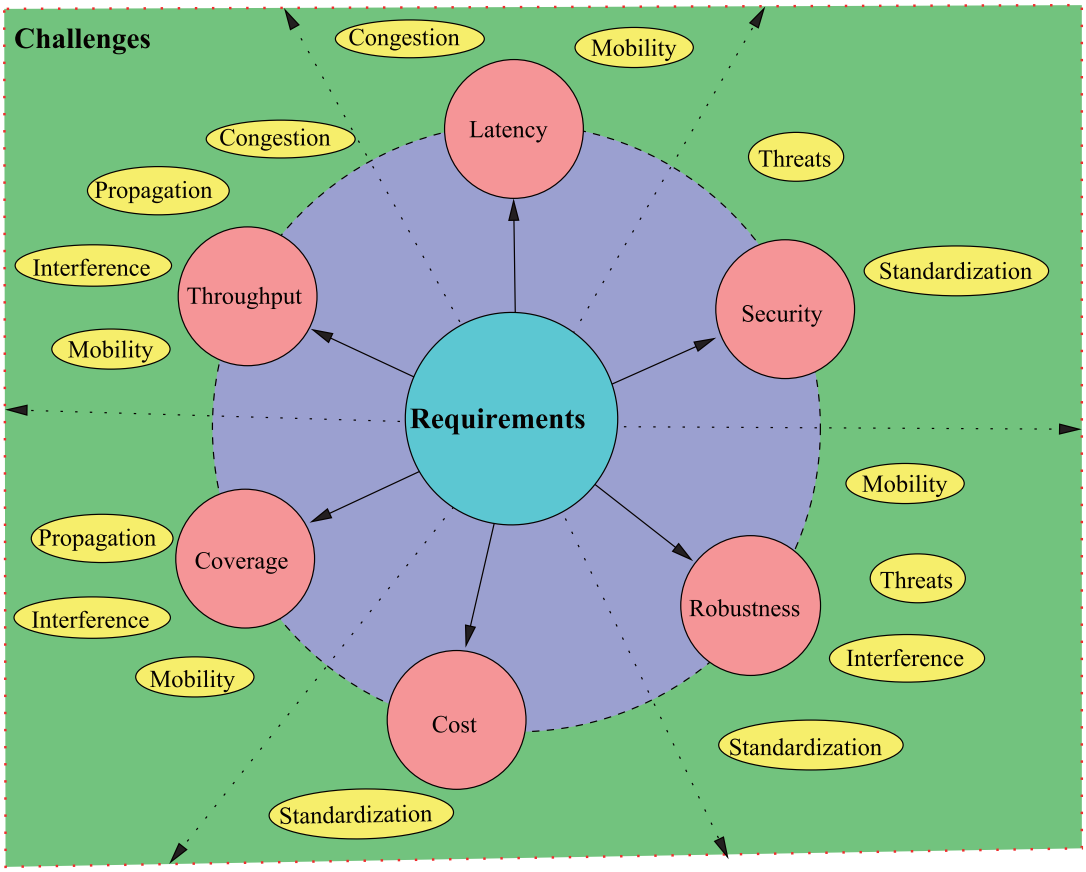


Fig. 13. *Challenges of AANET imposed by the requirements.*

on multiple bands when it exchanges information with a gateway deployed on the ground or a satellite for relaying its information. In order to characterize the channel illustrated in Table 3, we present the received SNR and the corresponding CCDF of different mobility scenarios by considering multiple antennas deployed on aircraft. As illustrated in Figs. 15 and 16, the aeronautical channel characteristics are significantly different for different scenarios, which impair the transmission signal quality. It is challenging to design transmission schemes, which can adapt to various propagation modes. Furthermore, it is also a great challenge to accurately model these propagation characteristics, consisting of the signal attenuation and phase variation statistics, the fading rate, the Doppler spread, and the delays during wave propagation [52], [148]. There are prohibitive cost constraints in the way of extensively measuring the aeronautical channel characteristics, especially for multiple access channels that suffer from interference among aircraft.

E. Interference

Another significant challenge is imposed by preventing mutual interference between aeronautical communications and terrestrial wireless communications, when an aircraft is flying over populated areas, especially near an airport [96]. The potential mutual interference must be mitigated so that the AANETs can adapt to diverse international standards and the specific implementations across the global airports. The detrimental effects of both multipath interference and of cochannel interference tend to increase the noise floor, hence reducing the capacity of the communication system, especially in the high traffic density environments near airports. In addition, multipath interference may occur due to propagation through frequency-selective fading channels, while cochannel interference may arise when signals are mapped to the same carrier frequency. Therefore, it is desirable to characterize the behavior of the various sources of interference in order to maintain high-integrity transmission, especially in safety-critical aeronautical applications [149].

F. Standardization

Various existing wireless standards defined for aircraft communications [96] have already existed for decades. However, there are more disparate requirements for A2A, A2G, and A2S communications, as mentioned in Section V. It is expected that AANETs will require a new global standard for seamless aeronautical communications [150]. Therefore, multinational cooperation will be necessary and the system has to be sufficiently flexible. In the light

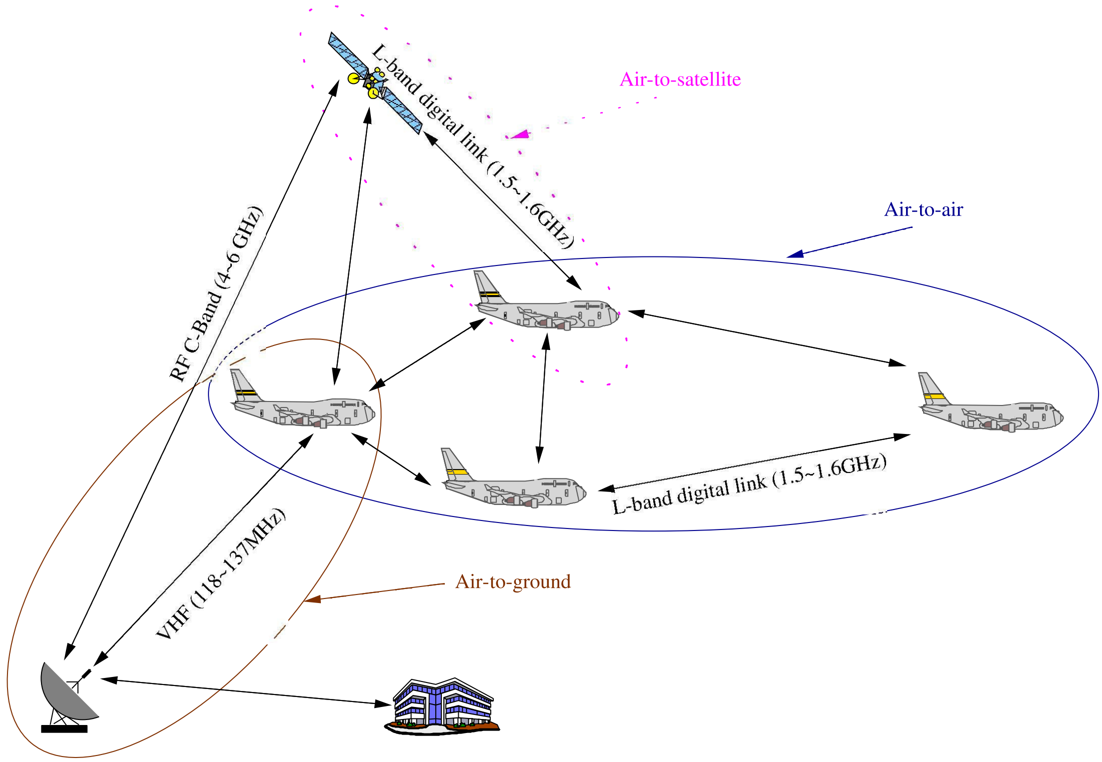


Fig. 14. ***Spectrum used for various aircraft communication systems.***

of the associated risks, it is challenging to gain regulatory approval from the various countries for such a safety-critical system and to persuade airlines to install the system on their aircraft. It is also a vital prerequisite that sufficient aircraft join the AANETs so that multihop relaying of other aircraft transmissions becomes feasible.

VIII. EXISTING RESEARCH IN ADDRESSING THE AANET CHALLENGES

In this section, we will review the proposals and techniques devoted to addressing the challenges of aircraft networking. The proposals and techniques discussed may simultaneously address several challenges.

A. Mobility Solutions

Since FANETs support high-mobility nodes and often are mission-oriented, their mobility model has to be flexible to have paths planned in advance or adapted online during the mission, in order to maximize the coverage or avoid collision [151]. Similarly, due to the high mobility of the aircraft, their mobility characteristics have a significant effect on the AANETs' mobility model. However, aircraft usually fly at a high velocity, and along a predesigned route, which specifies the corresponding mobility model [152], as shown in Fig. 7. Explicitly, the large-scale mobility pattern is randomly distributed for the case of aircraft above-mentioned continents since the airports are randomly distributed over the continent. By contrast, aircraft flying over oceans and other unpopulated areas can be identified as pseudolinear, rapidly moving mobile entities [8], [153], since they are all headed for partic-

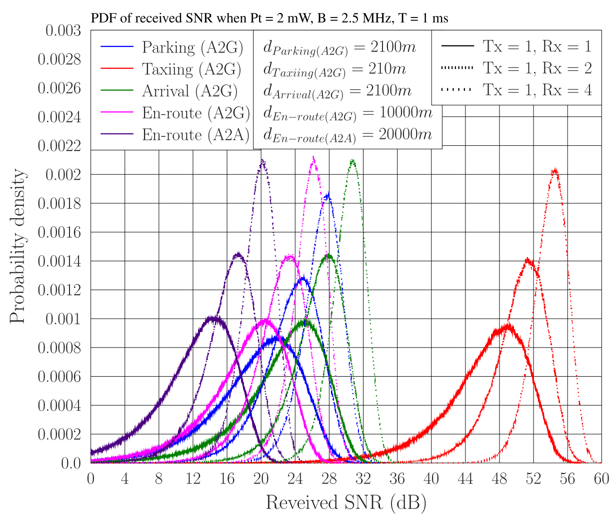


Fig. 15. ***Probability density of received SNR for different flight phases. Both the large-scale fading and small-scale fading have been considered. The channel parameters are set according to Table 3.***

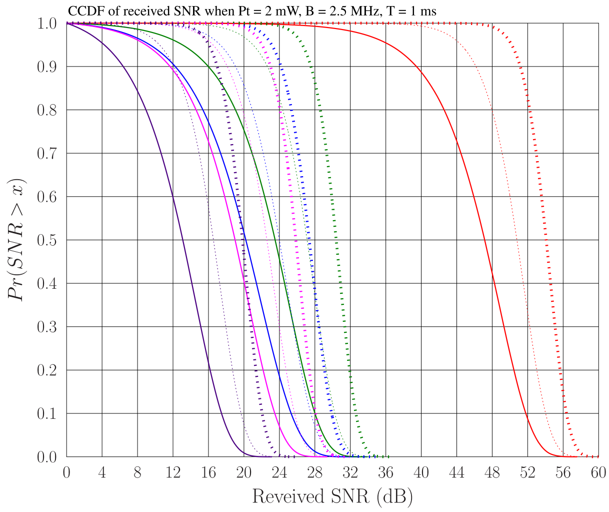


Fig. 16. ***CCDF of the received SNR for different flight phases. Both the large-scale fading and the small-scale fading have been considered. The channel parameters are set according to Table 3.***

ular populated regions, as seen in the scenario of the North Atlantic in Fig. 5. In addition, a clustering mobility model was established in [8] and [153] by considering aircraft originating from the same source and heading in the same general direction. Furthermore, Ghosh and Nayak [154] considered the 3-D aircraft topology in 3-D airspace for mitigating the effects of network disruption. Taking into the account specific flight phases and the speed of the aircraft, Li *et al.* [155] proposed a smooth semi-Markov mobility model, which divided the motion of aircraft into flight phases, as shown in Fig. 7. Petersen *et al.* [156] further developed the Markov mobility model by taking into account the traffic demand in a certain area, where they modeled both the arrival and departure of an aircraft in any of the states as a Poisson distribution in the developed Markov mobility model. In order to allow passengers to access the Internet, the architecture of AANETs has to support high-velocity mobility. The Internet is based on the IP to deliver information, and thus, the potential solutions conceived for providing Internet connectivity include the so-called network mobility basic support protocol of TCP/IPv6 [157], [158] and the host identity protocol [159]. The preferred solution may be host identity protocol, considering its flexible interoperability, since it could smoothly connect to the Internet and support mobility, as well as provide security and privacy [160].

B. Scheduling and Routing

Given the multihop nature of AANETs, the packets have to follow multiple wireless paths to arrive at their final destination. As discussed in Section VII, the scheduling and routing strategy has to be investigated for avoiding congestion and for achieving the maximum throughput per aircraft. Luo and Wang [161] proposed a reliable user datagram protocol relying on fountain codes. Furthermore, they have also developed a reliable multipath routing protocol [162] relying on multiple aeronautical networks capable of operating under challenging networking conditions. Furthermore, a number of research projects have investigated scheduling and routing algorithms conceived for AANETs. Sakhaee [8] and Sakhaee and Jamalipour [55] proposed a routing protocol by taking into account the Doppler frequency in the routing procedure. Furthermore, Sakhaee [8] integrated a QoS constraint into the cost metric of the routing protocol in his Ph.D. dissertation. Luo and Wang [163] further developed a QoS-based routing protocol by taking into account the path availability period, the residual path capacity, and the path latency in their route selection. Iordanakis *et al.* [164] proposed an *ad hoc* routing protocol for aeronautical MANET by combining the proactive function of *ad hoc* on-demand distance vector and the reactive function of topology broadcast based on reverse-path forwarding [165]. Medina *et al.* [22], [70] proposed to exploit the position information for assisting routing, and they assessed the proposed position-based greedy forwarding algorithm, which demonstrated that all packets were delivered to their destination with a minimum hop count. A sophisticated routing scheme was proposed by Gankhuyag *et al.* [166], which exploited both location-related and trajectory-related information for establishing their utility function, taking into account both the minimum expected connection duration and the hop count. Meanwhile, Wang *et al.* [167] and Saifullah and Kim [168] also designed their geographical routing protocols based on the knowledge of location information, which is assumed to be provided by ADS-B. Considering the balance between the capacity and traffic load of each A2G link, Medina *et al.* [43], [49] also developed a geographic routing strategy by forwarding packets to a set of next-hop candidates and spreading traffic among the set based on queue dynamics. Furthermore, Hoffmann *et al.* [147] developed a joint routing and scheduling scheme for AANETs, which sequentially minimized the weighted hop-count subject to scheduling constraints and minimized the average delay for the previously computed routes. Similar to the solutions in [22] and [70], Tiwari *et al.* [169] proposed a mobility-aware routing protocol by exploiting the known trajectories of the aircraft to enhance the attainable routing performance. Furthermore, Vey *et al.* [170] proposed a node density and trajectory-based routing scheme, which exploited the knowledge of the geographic path between the source aircraft and the destination aircraft and considered the actual aircraft density as well as Zhong *et al.* [171] also exploited the density of aircraft as well as the geographic path between the source node and the destination node for routing. Peters *et al.* [172] developed a geographic routing protocol termed as the aeronautical routing protocol for multihop routing in AANET, which delivers packets to their destinations in a multi-Mach speed environment using velocity-based heuristics. By contrast, Dong *et al.* [173] proposed a topology-based routing mechanism for AANETs, which can effectively decrease the probability of routing path breakup, regardless of how high the aircraft density is.

C. Security Mechanisms

In order to guarantee the security of the aviation network while providing Internet connectivity for the passengers, the separation of the passenger, crew, and control networks has been widely recommended [68], [69], [174]. However, there is still a high risk of "cyber-PHY" security breaches [175], since the safety of air flight depends on data communication, which may suffer from attacks both by remote and onboard devices [73].

Research efforts have been launched for addressing the security issues in AANETs. Sampigethaya *et al.* [176] presented some security standards developed for in-aircraft networking [177], for electronic distribution of software [178], for onboard health management [179], and for ATC [39]. Mahmoud *et al.* [180] reviewed security mechanisms designed for aeronautical data link communications. Moreover, an IP-based architecture has been recommended for future aeronautical communications in [25] and [150], and security architectures conceived for the IP have received a significant amount of attention by the SESAR. IP security [181] is one of the most popular solutions since it operates at the network layer, which makes it suitable for different applications employing different transport layer protocols [69]. However, the investigation in [69] indicated that SSL/TLS-based security mechanisms are capable of providing a level of security almost equivalent to IP security without reducing the QoS. Furthermore, AANETs may have to exchange information among aircraft belonging to different airlines for maximizing the aircraft connectivity, which imposes airline confidentiality issues. In order to resolve these security issues, Mahmoud *et al.* [182] proposed a secure geographical routing protocol by exploiting the benefits of the greedy perimeter stateless routing in [183] and of the ADS-B protocol. Nijsure *et al.* [184] developed AOA, TDOA, and FDOA techniques in order to provide additional safeguards against ADS-B security threats and for aircraft discrimination. Furthermore, Nijsure *et al.* [184] also implemented a software-defined-radio-based hardware prototype for facilitating AOA/TDOA/FDOA. Since the ADS-B messages can be received by any individual ADS-B receiver, this results in substantial security concerns for ADS-B-based communication systems. Baek *et al.* [185] proposed an identity-based encryption scheme by modifying the original identity-based encryption of Boneh and Franklin [186]. He *et al.* developed the triple-level hierarchical identity-based signature scheme in [187] for practical deployment. A range of further security protocols designed for ADS-B systems may be found in the excellent survey in [87].

D. Aeronautical Channel Characterization

Aeronautical communications involve A2G, A2A, and A2S communications at airports, populated areas, and unpopulated areas. The accurate knowledge of the channel characteristics is important for carefully designing and assessing the performance of aeronautical communication protocols, which motivates the research devoted to characterizing the aeronautical channel.

Explicitly, Bello [188] investigated the aeronautical channel between aircraft and satellites, focusing on the effects of indirect paths reflected from and scattered by the surface of the Earth. His work was then further developed by Walter and Schnell [189] by characterizing the A2A propagation characteristics, while the scattered components of an aeronautical channel were investigated in terms of its delay and Doppler frequency in [189]. In contrast to investigating the A2A channel, Haas [52] devoted his efforts to A2G aeronautical channel models. As a further development, the A2G aeronautical channel at 5.2-GHz RF was measured by Gligorevic [190] at Munich airport. The A2G aeronautical channel over the ocean's surface was measured by Lei and Rice [191] at 8.0 GHz and by Meng and Lee [192] at 5.7 GHz, respectively. Facilitated by the development of multiple-antenna technologies in wireless communications, the corresponding radio propagation characteristics were analyzed in [193] for Alamouti's STBC scheme in [194].

Moreover, research efforts have been invested in analyzing the channel capacity of aeronautical channels and the performance of diverse modulation schemes over aeronautical channels [195] as well as in mitigating the effects of Doppler shifts [196].

E. Interference Mitigation

A mature aircraft communication system has to be able to mitigate interference, since this limits the achievable capacity, hence also imposing safety risks. In the case of FANETs, awareness of the primary and associated spectrum reuse relying on spectrum sensing is extremely crucial for interference avoidance between the primary users and secondary users [197].

Extensive efforts have been devoted to mitigating the multipath interference [198], the cochannel interference [149], [199], [200], the multiple access interference [49], [201], [202], and the mutual interference between different wireless communication systems [57], [73], [203]. More specifically, Popescu *et al.* [198] proposed a linear equalizer based on Kalman filtering theory for mitigating the multipath interference and adjacent-channel interference. The cochannel interference characteristics encountered in a high-density traffic environment were analyzed in [149] by using computer simulations, and a multiuser detection scheme was recommended for mitigating cochannel interference. By contrast, Tu *et al.* [201] characterized the multiple-access interference in a sparse air traffic environment, judiciously managing the inter-

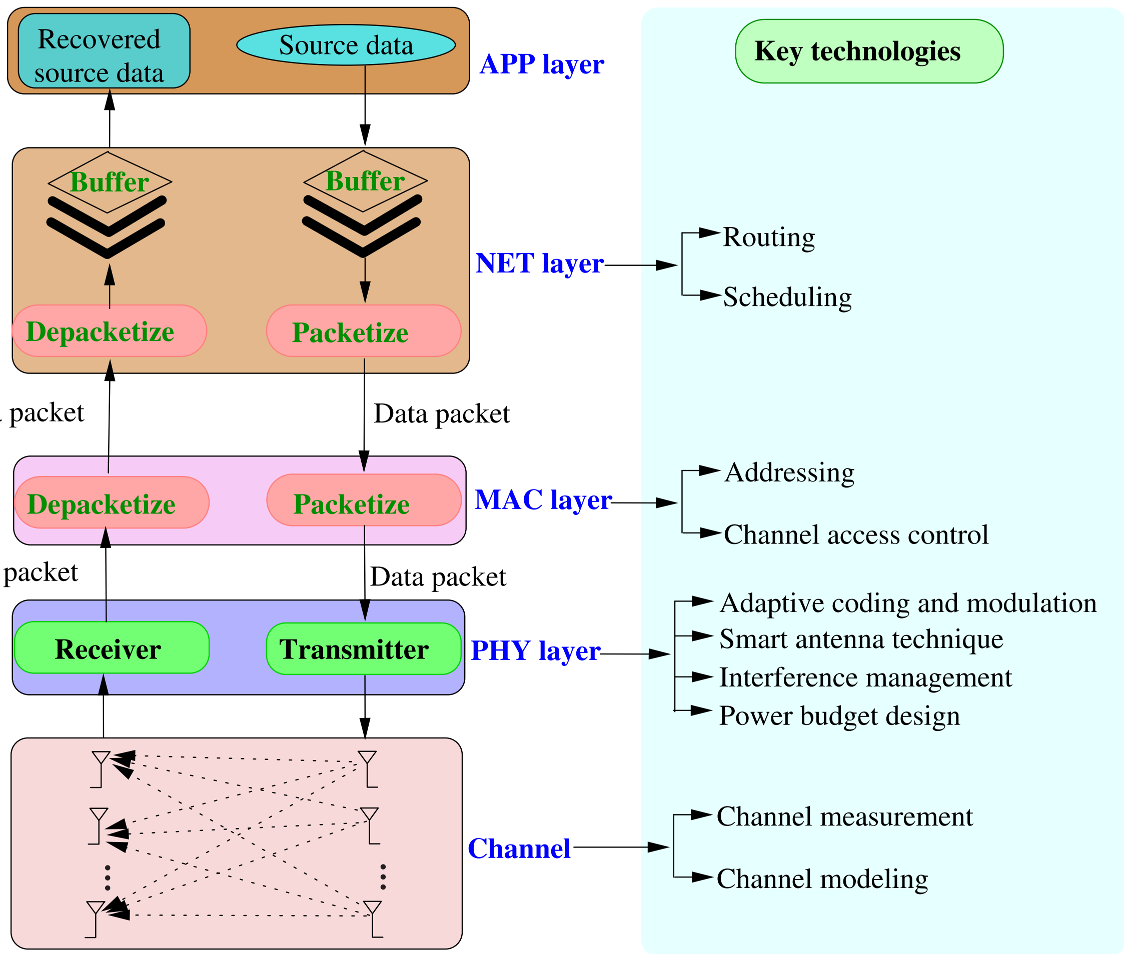


Fig. 17. *Design guideline for AANETs.*

ference power with the aid of feedback information. Medina *et al.* [49] recommended sophisticated scheduling for channel access in a TDMA regime for mitigating the multiple access interference. As a further development, Fang *et al.* [204] proposed a hybrid MAC protocol based on preallocation of the transmission time slots carefully combined with random access for mitigating the collision probability. Besse *et al.* [202] developed an optimized network engineering tool model to analyze the impact of multiple access interference on the packet delivery probability, concluding that the solution could be either to reduce the transmission rate in order to reduce the interference effects or to use a dedicated channel while having severe cochannel interference. In order to reduce the interference imposed on HF communications by other communication systems and that imposed on the communications between ATC controllers and pilots, Tu and Shimamoto [57] proposed a TDMA-based multiple-access scheme for transmitting an aircraft's own packets and for relaying the neighboring aircraft's packets. Kamali and Kerczewski [203] investigated the potential interference imposed by the AeroMACS on the MSS feeder link in an airport environment, recommending the adaptive allocation of frequencies to different cells using a variable frequency reuse factor. By contrast, the interference imposed both by passenger devices and by intentional jamming were discussed in [73], with an emphasis on the aviation safety.

F. Efforts for Standardization

As discussed in Section VII, the standardization of aircraft communication is more complex than a pure technical challenge since it has to balance many other factors, as well such as numerous practical issues, spectrum regulation, and national security. Because of this, it cannot be achieved by a single community or country. At the time of writing, the standards for aeronautical communications are mainly issued by the ICAO and FAA in the United States, and by the EUROCONTROL in Europe, given their leading roles in aviation. More specifically, the FAA has funded NextGen [205] for conceiving the future national airspace system in the United States Meanwhile, the European Commission and EUROCONTROL have jointly funded

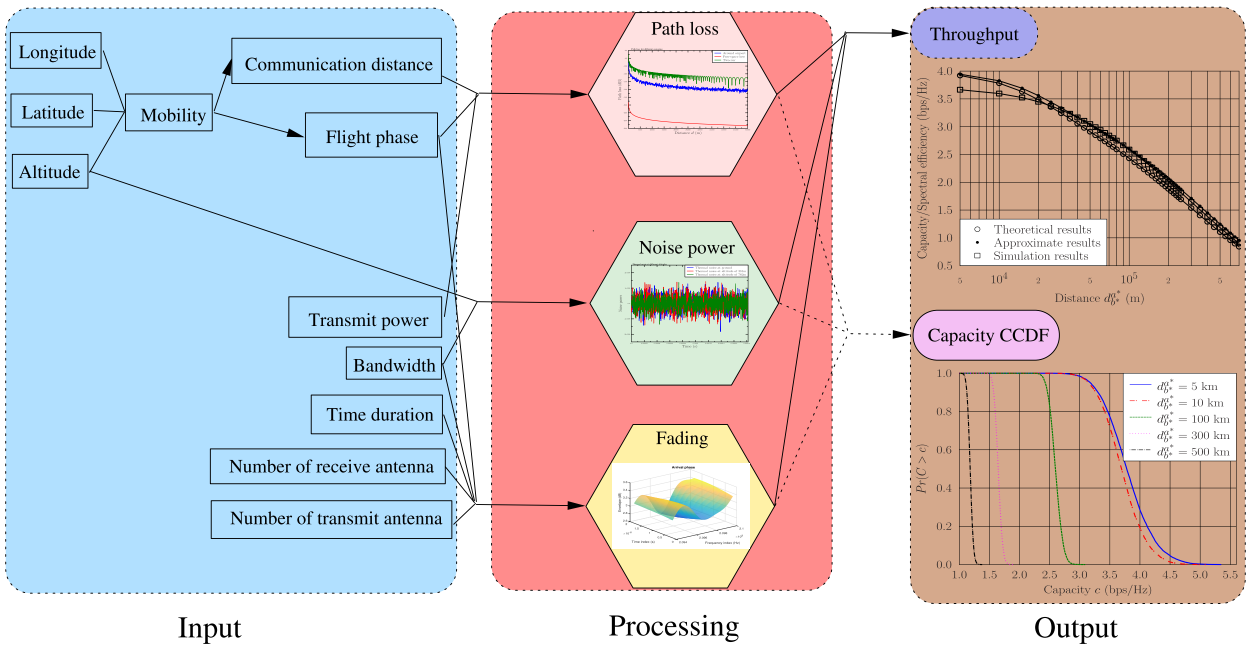


Fig. 18. *Aeronautical channel propagation.*

SESAR [206] for improving the future ATM in Europe. However, the flourishing development of aviation in recent decades has inspired more nations to devote research to aviation. Motivated by this, Neji *et al.* [4] appealed for multinational cooperation of establishing international standards. Along these lines, FAA and EUROCONTROL initiated a joint study in the framework of Action Plan 17 [89] to investigate applicable techniques and to provide recommendations for future aircraft communications [106], which paves the way for an international standard to be accepted by both the United States and Europe.

IX. DESIGN GUIDELINES FOR AANETs

In this section, we outline the key techniques of AANETs along with our design guidelines for the four-layer protocol stack, namely, for the PHY layer, MAC layer, NET layer, and APP layer, as shown in Fig. 17.

A. Channel and PHY Layer

Explicitly, the propagation channel of aeronautical communication is intricately linked to the aircraft mobility, which captures the PHY movement patterns of aircraft. Since field measurements would be extremely expensive for passenger planes engaged in different maneuvers in different network scenarios, stochastic and/or semistochastic mobility modeling may be more realistic solutions. However, random mobility modeling [207] typically used in FANETs may fail to accurately characterize AANETs since the passenger airplanes' routes are typically preplanned; hence, preplanned semistochastic mobility models may be developed for AANETs.

The wireless channel characterized in the middle of Fig. 18 imposes distance-dependent path loss effects as well as from small-scale fading due to reflections/scattering and Gaussian-distributed the background noise. Explicitly, apart from the communication distance, the path loss also depends on the specific flight phase of take-off/arrival, parking, and en-route. Given the transmit power, the position information, bandwidth, the number of transmit antennas, and the number of receive antennas and a number of other parameters seen at the left of Fig. 18, we can characterize the corresponding aeronautical channel, which directly determines the achievable throughput, as illustrated in the right-hand section of Fig. 18.

To elaborate a little further in technical terms, based on the channel characterization and on our regularized zero-forcing transmit precoding (RZF-TPC) scheme shown in [200], we could design an distance-based ACM [199] for the A2A aeronautical communications system having seen different-rate ACM modes, as shown in Table 10. The corresponding system capacity versus distance is shown in Fig. 19. Explicitly, based on the distance $d_{b^*}^{a^*}$ between aircraft a^* and b^* measured by its distance measuring equipment, aircraft a^* selects an ACM mode for data transmission according to

$$\text{If } d_k \le d_{b^*}^{a^*} < d_{k-1}: \text{ choose mode } k, \quad k \in \{1, 2, \dots, K\}.$$

Assuming that the maximum communication range is $D_{\max}$, which can be determined by the parameters in the left-hand section of Fig. 18, no communication is provided for $d_{b^*}^{a^*} \ge D_{\max}$, since the two aircraft are beyond each

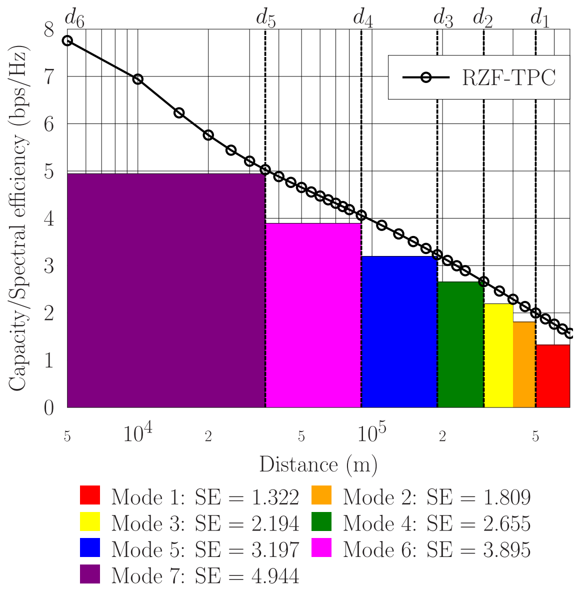


Fig. 19. ***Illustration of designing the RZF-TPC aided and distance-based ACM scheme.***

others' communication range. Moreover, the minimum flight-safety-based separation must be obeyed; hence, the minimum communication distance $D_{\min}$ obeys the minimum separation according to the ICAO's regulations.

B. MAC Layer

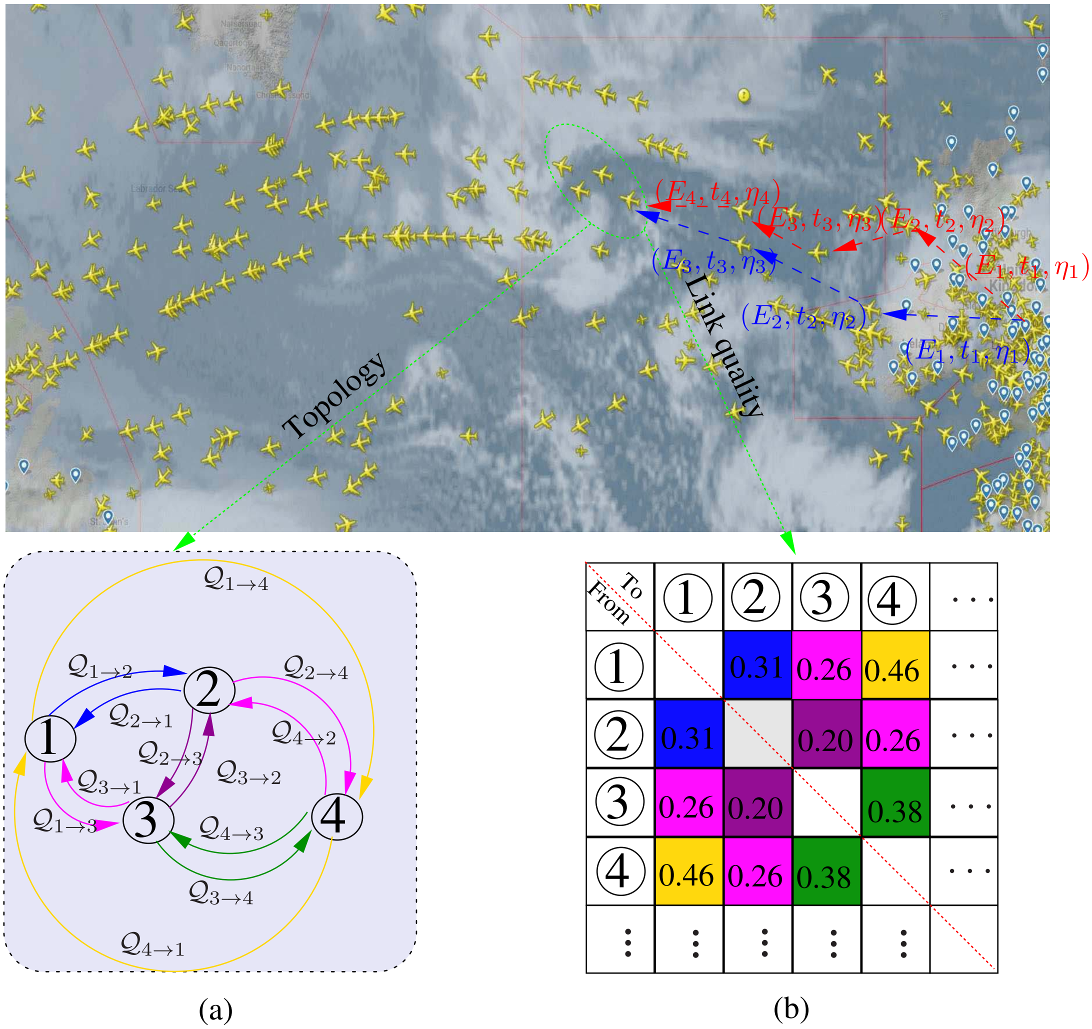
The MAC layer takes care of the channel access control mechanisms that make it possible for several nodes to communicate using a shared medium, without suffering from packet collisions transmitted by different nodes. In AANET scenarios, the combination of having limited wireless spectrum, low latency requirements, and high mobility impose significant challenges on the MAC layer. Furthermore, the MAC protocol is expected to support diverse network topologies that vary dynamically owing to the high velocities of aircraft nodes. The MAC layer also has to avoid relying on an excessive number of RF chains operating on different frequencies in an FDD manner, which would be unsuitable for aircraft installation. Alternatively, TDD may facilitate multiple nodes to access a shared medium [208]. Explicitly, only a single node having the token at any instant is allowed to transmit data and then it has to pass the token to another node for avoiding collisions of different nodes transmitting at the same time. This approach maintains reliable and fair access to the network, as well as achieving a high degree of efficiency, flexibility, and robustness in the medium access control and topology management.

However, in traditional token-based MAC protocols, when a node joins the ring, it is required to negotiate a position in the ring in order to identify a predecessor and a successor node, which are also required to accordingly update the identity of their successor and predecessor node, respectively. Likewise, when a node leaves the ring, its predecessor node and successor node must update the identity of their successor and predecessor nodes accordingly. A large amount of coordination and control information must be passed around the network, hence resulting in a high overhead and low efficiency, when the network topology varies rapidly with nodes joining and leaving frequently, which imposes challenges on AANETs, especially because the aircraft nodes have high velocities, leading to a dynamically evolving topology.

Given the unique features of AANETs, we may advocate a mesh topology-aware token passing management with an associated link quality table, as shown in Fig. 20, where the color represents the link quality as illustrated in Fig. 19, while the value in the table is the routing cost. To elaborate a little further, the routing cost may be quantified in terms of many different metrics for evaluating a routing protocol, such as the number of hops, delay, reliability, and throughput, just to name a few. In general, this multicomponent optimization problem becomes quite complex, especially for networks having many nodes. The best approach is to find the Pareto-front of all optimal solution. More explicitly, the Pareto front is the collection of all the operating points, which have the minimum BER, delay, power consumption, and so on. None of the Pareto-optimal solutions may be improved, say in terms of the BER without degrading either the delay, or the power-efficiency, or the complexity, etc. Nevertheless, here, we consider the single-component spectral efficiency optimization for establishing the routing cost table for exemplifying the basic philosophy of our proposed mesh topology-aware token passing management. Consider the four-node mesh network shown in Fig. 20 as an example, where the routing cost table is a (4×4)-element table, where the element in the ith row and the

Table 10 Design Example of RZF-TPC Aided and Distance-Based ACM With $N_t = 64$ and $N_r = 4$

Mode k	Modulation	Code rate	Spectral efficiency (bps/Hz)	Switching threshold d_k (km)	Data rate per receive antenna (Mbps)	Total data rate (Mbps)	Routing cost $\mathcal{Q}$ (s·Hz/bit)
1	QPSK	0.706	1.323	500	7.974	31.895	0.76
2	8-QAM	0.642	1.813	400	10.876	43.505	0.55
3	8-QAM	0.780	2.202	300	13.214	52.857	0.45
4	16-QAM	0.708	2.665	190	15.993	63.970	0.38
5	16-QAM	0.853	3.211	90	19.268	77.071	0.31
6	32-QAM	0.831	3.911	35	23.464	93.854	0.26
7	64-QAM	0.879	4.964	5.56	29.783	119.130	0.20



From \ To	1	2	3	4	⋯
1		0.31	0.26	0.46	⋯
2	0.31		0.20	0.26	⋯
3	0.26	0.20		0.38	⋯
4	0.46	0.26	0.38		⋯
⋮	⋮	⋮	⋮	⋮	

Fig. 20. *Example topology of AANET consists of four nodes and their corresponding routing cost table. "⋯" means the routing cost table is expandable according to the number of nodes. (a) Topology link quality. (b) Link quality.*

jth column identifies the quality of the link spanning from the ith node to the jth node, where the color represents the link's spectral efficiency, as shown in Fig. 19. The routing cost $\mathcal{Q}$ is defined as the reciprocal of the spectral efficiency. For example, the link leading from node 1 to the node 2 in the routing cost table of Fig. 20 has a link quality represented by blue color, which results in a routing cost of $\mathcal{Q} = 1/3.197 = 0.31$. Note that the links between the nodes are bidirectional and may be asymmetric, resulting in a different link quality marked by different colors between the elements having the indices (i, j) and (j, i) in the link quality table. However, in our example, we assume simplicity that the link quality of two nodes is symmetric based on the fact that the link quality in A2A aeronautical communication is dominated by the communication distance.

The link quality table will then be used both by the MAC layer and by the NET layer. In the MAC layer, the link quality table is used in conjunction with the token roll count to select which particular node will pass the token to the next one. When a node's MAC layer has a token, it will ask the NET layer to provide a set of data packets and to specify the spectral efficiency used.

C. NET Layer

In the network (NET) layer, scheduling and routing determine the multihop paths to be followed by the packets between their source and destination nodes. More specifically, each hop to be taken by the data packets is decided dynamically and opportunistically at each stage of the multihop path rather than being decided by the source node. In particular, each packet may be received by more than one node and then forwarded by whichever has the first opportunity to transmit. This dynamic, opportunistic, and redundant approach to routing improves the network's robustness to rapidly changing topologies, which is one of the main challenges for routing in AANETs.

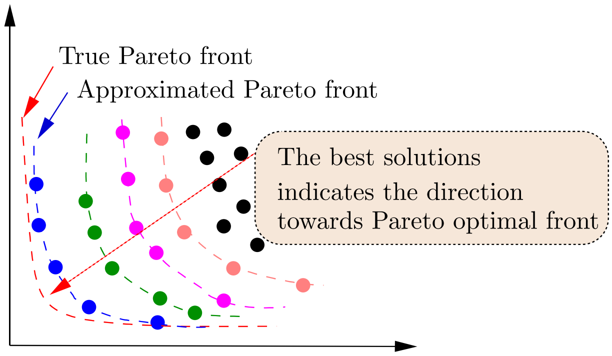


Fig. 21. ***Example of optimal Pareto front for two objective optimization problems.***

The cost of a multihop path is given by the sum of the costs of its constituent links. For example, the path shown in Fig. 20 starting from node 1 and passing through node 3 on to node 4 is denoted as $1 \rightarrow 3 \rightarrow 4$, which has a cost calculated as $\mathcal{Q}_{1\rightarrow3\rightarrow4} = \mathcal{Q}_{1\rightarrow3} + \mathcal{Q}_{3\rightarrow4} = 0.26 + 0.38 = 0.64$. Alternatively, there are also other routing paths from node 1 to node 4, such as $\mathcal{Q}_{1\rightarrow2\rightarrow4}, \mathcal{Q}_{1\rightarrow2\rightarrow3\rightarrow4}, \mathcal{Q}_{1\rightarrow3\rightarrow2\rightarrow4}, \mathcal{Q}_{1\rightarrow4}$. Nevertheless, given the link quality table shown in Fig. 20, graph theory [209], relying for example on tree algorithms, shortest-path algorithms, minimum-cost flow algorithms, etc., may be exploited for solving the problem of finding the lowest-cost multihop path spanning from the source node all the way to the destination node.

Still referring to Fig. 20, we further investigate the routing optimization problems. The mesh network consists of the four airplanes circled by the green dashed ellipse should have a complete connected path all the way to the control tower at London's Hearthrow airport for our example. To elaborate a little further, the transmission between a pair of nodes is assumed to incur an energy cost of E_i to impose a delay of t_i and to have a spectral efficiency of η_i. The cost function associated with a specific routing path contains the aggregate energy consumption $\sum E_i$, the aggregate delay t_i, and the end-to-end spectral efficiency of $\min\{\eta_i | i = 1, 2, 3, \ldots\}$, which is a multiobjective optimization problem determined by diverse factors. The multiobjective optimization problem can be solved using Pareto optimization techniques, which generate a diverse set of Pareto optimal solutions so that a compelling tradeoff might be struck among different objectives. An example of a twin-parameter Pareto-optimization problem is shown in Fig. 21, where all circles represent legitimate operating points and all blue circles represent Pareto optimal points, which are not dominated by any other solutions.

D. Pareto Optimal Perspective of AANET Optimization

Again, the design of ANNETs includes that of the PHY layer, MAC layer, NET layer, and APP layer, which faces substantial challenges in terms of meeting diverse objectives. Traditional single objective may be still used by iteratively optimizing each metric; however, it can only find a local optimum at a potentially excessive computational complexity, signal processing delay, and energy consumption. Moreover, the diverse optimization metrics of AANETs are typically not independent of each other, and they are mutually linked with each other in terms of influencing the overall system-level performance. It is also a challenge to provide an ultimate comparison among different locally optimal solutions based on different metrics, since the objectives involved ten to conflict with each other, hence requiring a tradeoff.

In contrast to the single-objective optimization, multiobjective optimization is capable of finding the global Pareto optimal solutions by striking a tradeoff among conflicting objectives. Explicitly, we summarize a range of popular metrics shown in Fig. 22 typically exploited in designing AANETs. Over the past decades, a number of research contributions have focused on addressing one or more objectives as well as jointly addressing a few objectives, as we have discussed in Section VIII. However, with the rapid improvement of the computational capability of cloud computing [210] and quantum computing [211], it enables us to systematically conceive cross-layer design and optimization with the aid of multiobjective optimization algorithms, as illustrated in Fig. 22. A more detailed comparison between different multiobjective optimization algorithms could refer to those in [212] and [213] and in the references therein.

X. PROSPECTIVE SOLUTIONS AND OPEN ISSUES

AANETs aim for building communication links among aircraft. However, they cannot be operated in isolation without satellites and GSs, which provide GPS signals or backhaul. Thus, the practical AANETs rely on multiple layers consisting of satellites, GSs, and aircraft while handling information dissemination across the multiple layers in heterogeneous environments, with the objective of meeting the stringent requirements of aeronautical communication in time-sensitive as well as mission-critical applications. The challenges were discussed in Section VII, and the state-of-the-art research contributions devoted to addressing these challenges were discussed in Section VIII. Nonetheless, there are many open issues and prospective solutions to be investigated.

A. Prospective Solutions for AANETs

1) *Large-Scale Antenna Arrays:* Large-scale MIMO [214] systems employ hundreds of antennas for serving typically a few dozen terminals while sharing the same time-frequency resources. This technique achieves a hitherto unprecedented spectrum efficiency, energy efficiency, as well as low latency. Hence, it is widely accepted as one of the key 5G techniques. Aircraft typically have a large airframe, which may be capable of accommodating

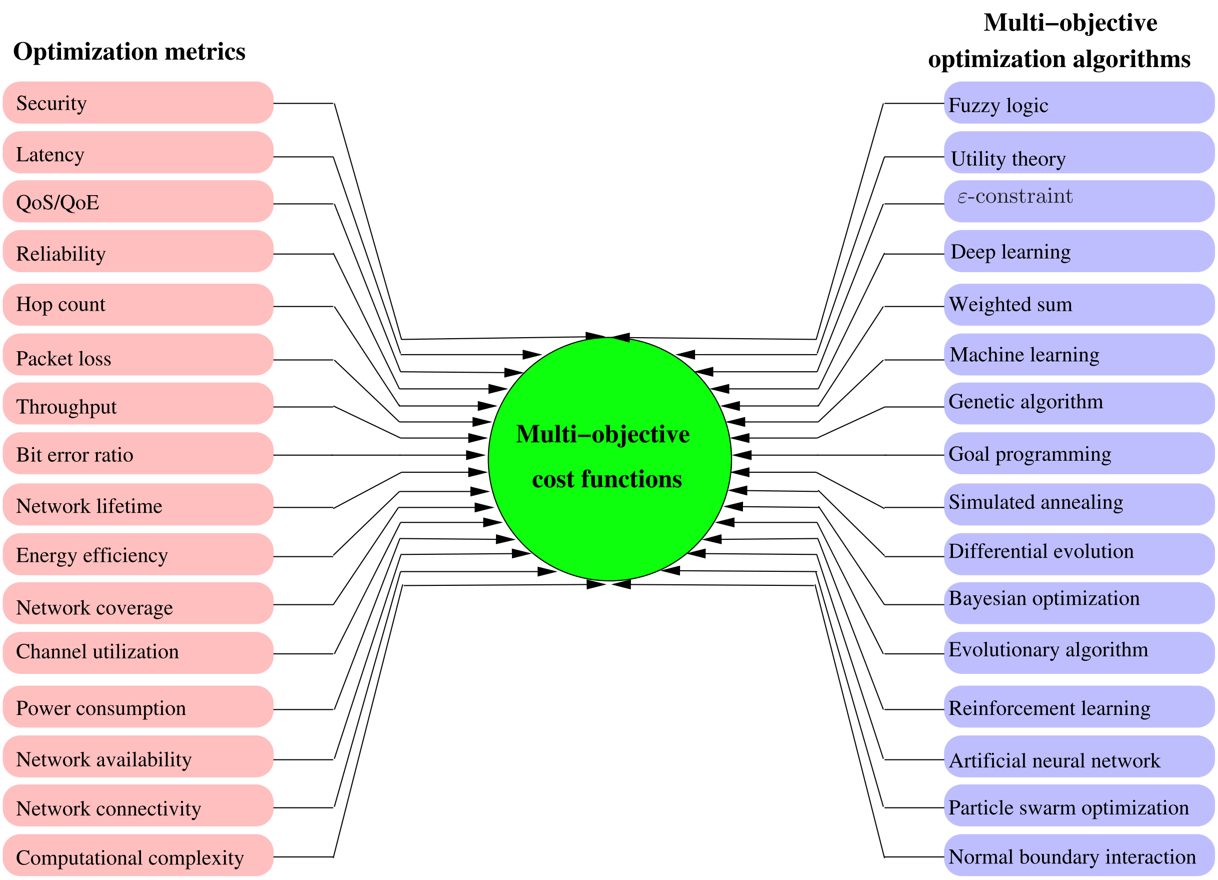


Fig. 22. *Potential metrics that may be used for optimizing AANETs and the multiobjective optimization algorithms that may be invoked.*

dozens of antennas. However, the deployment of large-scale MIMOs is not straightforward due to the form-factor limitation discussed in Section VII. It remains a challenge to fit dozens of antennas on commercial aircraft. The VHF band is widely used for existing aeronautical communication systems, but at these wavelengths, the required antenna spacing is high, which will limit the number of antennas that can be installed on the aircraft. Thus, the centimeter-wave carriers having a frequency ranging between 3 and 30 GHz has attracted intense investigations in aeronautical communication [52]. However, the antenna design is crucial due to the limited opportunity for their deployment and fuselage blocking. Motivated by this, conformal antennas[3] [215], [216] may be considered for the antenna design of aeronautical communications. Furthermore, to accommodate different scenarios, having diverse flight velocities and required throughput, both adaptive coherent/noncoherent and adaptive single/multiple-antenna-aided solutions [217] may also be conceived for aeronautical communications.

[3]Conformal antennas are flat radio antennas that are designed to confirm or follow some prescribed shape upon which they will be mounted.

2) *Free-Space Optical Communications:* FSO [107] communications constitute a promising technique that adopts LDs as transmitters to communicate, for example, between aircraft as well as between aircraft and a satellite at a high rate. Establishing their applicability to aircraft-ground communications requires further studies owing to its eye-safety concerns. The directional and license-free features of FSO are appealing in aeronautical communications because conventional RF communications are fundamentally band-limited. FSO communications have also been planned for the provision of connectivity for suburban/remote areas in Facebook's forthcoming project [218], as well as for connectivity between the Moon and Earth in NASA's Lunar laser communication demonstration project [219]. Advanced steered laser transceivers [220], which were originally designed for nano-satellites, may also be deployed on aircraft, GSs, and satellites for providing FSO communications between them. However, FSO communications are vulnerable to mobility because LOS alignment must be maintained for high-integrity communications. In order to solve the associated pointing and tracking accuracy problems for high-speed aircraft, a feasible solution is to rely on the built-in GPS system of the air-

craft, along with the FSO system's low transmission latency, which can also assist in formation-flying. Furthermore, since there are no obstacles in the stratosphere, the main disadvantage of terrestrial FSO links in terms of requiring a LOS channel becomes less of a problem. Thus, the FSO communication links among aircraft have a promising potential in terms of constructing an AANET for aircraft tracking and collision avoidance. Alternatively, the AANETs could also rely on FSO for the backhaul with the aid of GSs or satellites. Finally, since FSO and RF links exhibit complementary strengths and weaknesses, a hybrid FSO/RF link has a substantial promise in large-scale MIMOs.

3) *Heterogeneous Networks:* As shown in Fig. 1, an AANET consists of three individual layers, which may be viewed as a heterogeneous network (HetNet) that is composed of satellites, aircraft, and Internet subnetworks. It is quite a challenge to manage and optimize the whole plethora of metrics across multiple layers. The architecture of HetNets shifts the design paradigm of the traditional centrally controlled cellular network to a user-centric distributed network paradigm, which is suitable for emerging AANETs. To elaborate a little further, AANETs are capable of self-organization. They are autonomous and rely on diverse protocols as well as on potentially hostile communication links. In a HetNet of aircraft, different applications have different QoS requirements, security requirements, and user/operator preferences, which may require carefully designed data link selection [221], which is cognizant of to the particular transmission characteristics when constructing the sophisticated multilayered space-terrestrial integrated network of the future [222]. This can provide diverse communication services, such as safety-critical or nonsafety-critical communication services, or a combination of both. AANETs are also expected to support automatic node discovery and route-repair as well as to exchange cross-layer information among aircraft, satellites, and ATCs, which may be optimized by cross-layer gateway selection, as pioneered by Shi *et al.* [223] in the integrated satellite-aerial-terrestrial networks. This concept was further optimized by Kato *et al.* [224] using efficient artificial intelligence techniques. However, the high-mobility-induced dynamics of the aircraft topology impose challenges upon the design of the routing, scheduling, security protocols, and on IP management, as well as on cross-layer optimization [225] among the PHY, MAC, network, and transport layers. All these sophisticated, high-flexibility HetNet features should be evaluated in realistic scenarios, including typical airport scenarios as well as both populated and unpopulated areas, which requires substantial efforts from the entire research community [226].

4) *Cooperative Relay Communications:* Relaying messages among aircraft is a pivotal operation in AANETs, which is capable of increasing the coverage, throughput, and capacity of the AANETs. However, the optimization of the multihop routing is crucial for maximizing the achievable relay performance [221], [227]. Cooperative relay-aided communication [228] is easier to achieve among aircraft than among mobile phones since a mutually beneficial agreement might be easier to strike between airlines. Thus, cooperation constitutes a promising method to offer extra spatial diversity without requiring PHY antenna arrays. Moreover, storing packets and retransmitting them when there are favorable communication links is capable of improving the network's resilience, throughput, and diversity [229], which has motivated the research of buffer-aided relaying [230]–[232]. Aircraft, especially those belonging to the same airline or airline alliance, could exploit the buffer-aided relaying technique for improving their connectivity and throughput. As a further development of the buffer-aided idea, "Cache in the air" [233] can cache popular video/audio contents in intermediate servers, such as local servers, gateways, or routers. The concept of caching in the air can also benefit the aircraft network by significantly reducing the associated response latency and by sharing their navigation information as well as their weather conditions, which will enhance the flight safety by the prompt provision of precautionary information for collision avoidance and for storm/airflow warning. Moreover, efficient caching and sharing strategies are capable of supporting the creation of temporary social networks in and around airport lounges, aircraft, and so on.

5) *Cognitive Radio Communications:* The existing air traffic systems typically communicate in the VHF band (108–137 MHz) and the HF band (2.85–23.35 MHz). Apart from surveillance radar and aeronautical navigation systems, the UHF band has almost entirely been allocated to television broadcasting and cellular telephony. It is crucial to guarantee interference-free access for these aeronautical communication systems due to the safety of life. However, it can be foreseen that the wireless teletraffic of aeronautical communications will rapidly be increasing due to the tremendous growth of the aviation industry, which imposes pressures due to the scarcity of spectrum. Furthermore, unmanned aerial systems also aggravate the spectrum scarcity in the aeronautical domain [234]. Yet, no new aeronautical spectrum assignments can be expected within the immediate future due to the limited availability of wireless spectrum. AANETs mainly exchange information via multihop A2A communication, which may rely on the SHF

band spanning from 3 to 30 GHz [199]. Historically, separate allocations have also been made for aeronautical surveillance systems and aeronautical navigation systems. However, it remains quite a challenge to support the ever-increasing demand for wireless access in aeronautical communications without conceiving efficient techniques for spectrum reuse. Thus, there is a growing tendency and impetus toward sharing radio spectrum between radio services, provided that there is no excessive interference. CR [235], [236] is an emerging paradigm for efficiently exploiting the limited spectral resources. CR offers an efficient solution to reuse the existing spectrum without license, which has attracted wide attention in aeronautical communications [237], [238]. However, robust spectrum sensing is required in aeronautical communications, since packet collisions in spectrum usage may lead to catastrophic consequences during landing/takeoff [234]. Thus, the probability of missed detection must tend to zero. Furthermore, the lifetime of the just detected available spectrum should also be carefully investigated, since the speed of aircraft is high as they can fly at about 16 km per minute. Moreover, integrating and exploiting noncontiguous frequencies is crucial for providing high throughput broadband Internet access for aircraft. In addition, a robust handover strategy between frequencies should be designed in order to provide smooth and continuous service, especially for mission-critical communications.

B. Open Challenges in the AANET Implementation

1) *High Data Rate:* Providing high-rate Internet access for hundreds of passengers in the cabin of a commercial aircraft remains a significant challenge since it demands extremely high data volume per aircraft. Existing systems mainly use satellite-based solutions, in order to provide global connectivity, although this suffers from a low data rate and high cost. A2G stations have been widely deployed both in the USA and in Europe, which have provided faster Internet access and lower cost, but their coverage is limited to the European/North America airspace and the total data volume still remains low. AANETs are capable of extending the coverage of the A2G stations designed for aeronautical communications, but the aircraft have to employ radically improved transceivers for facilitating high data rates. The above-mentioned large-scale MIMO aided adaptive modulation scheme is capable of providing up to 76.7-Mb/s A2A data rate, using a configuration of 4 receive antennas and 32 transmit antennas [199]. Thus, large-scale MIMO schemes constitute a promising solution of providing high data rates for aeronautical communications. Moreover, FSO communication is also a competitive solution for providing high data rates, but the laser safety and steering accuracy issues must be addressed [107].
2) *Stable Connectivity:* Maintaining reliable connectivity is fundamental for AANETs to achieve data delivery. The connectivity among aircraft is a function of velocity, position, direction of flight, range of communication, and congestion [71]. Due to the highly dynamic nature and larger-scale geographic distribution of high-speed aircraft in contrast to terrestrial wireless communications, AANETs are facing a great challenge in terms of establishing stable multihop connectivity among aircraft [153]. This challenge is further aggravated by the often unpredictable mobility patterns, the high velocity, and the potentially high number of aircraft within a communication range, as discussed in Sections VII-A and IV-C, respectively. Thus, the routing protocols designed for aeronautical communications should cater for the specific requirements of AANETs and exploit the distinct characteristics of AANETs, as discussed for example by Sakhaee and Jamalipour [153], Medina and Hoffmann [6], and Medina [7]. New strategies, concepts, and metrics are required for designing the network protocols, which remains an open research challenge. For example, the probability of an aircraft becoming isolated can be considered for analyzing the connectivity of AANETs.
3) *Testbed Sharing:* Aeronautical communications are safety-related, especially in the context of ATC, formation flight, and free flight, which requires strict validation of any developed function and technique of AANETs. Thus, creating testbeds representing a proof-of-concept prototype is essential for maturing the technique of AANETs. Having an open testbed would be beneficial for both the academic research community and for the commercial development of AANETs. However, it is challenging to develop an integrated and robust testbed for AANETs, which relies on an aircraft mobility simulator, PHY layer, data link layer, and network layer emulations. Moreover, it also faces the challenge of the high cost of developing the testbed. Both the NASA research center [239] and the German aerospace center [158] have invested significant efforts in developing their testbeds. However, these testbeds have not been opened for public use not even for academic research.
4) *Global Harmonization:* Various proposals have been conceived for aeronautical communications by individual countries, which have obtained ICAO approval independently of each other. However, none of them have achieved global endorsement. In order to achieve seamless aeronautical communications among aircraft originating from different countries/airlines, an evolutionary approach toward global interoperability has to be developed. For this

reason, multinational cooperation will be necessary for prescreening, investigation and harmonization of the shortlist of competing technologies.

5) *Compatibility:* An AANET is capable of supporting direct A2A communication among aircraft without the assistance of GSs/satellites and ATCs, which reduces the teletraffic pressure imposed on them and significantly reduces the latency of critical-mission communication as well. Nonetheless, the aircraft should regularly communicate with ATC. Thus, AANETs must be capable of operating in the presence of interference, while imposing only an acceptable level of interference on the legacy aviation systems to avoid jeopardizing flight safety. Hence, it is necessary to evaluate the RF compatibility of the AANETs of the future with the systems already in operation both in A2G and in A2S communications.

6) *Deployment:* There has to be a certain minimum number of aircraft in the air in order to make the network usable. Thus, a certain minimum number of aircraft has to participate in the AANET before its benefits may be quantified. The gestation period of aircraft from a new technology launch to its entry into service is typically 10–15 years, which is significantly longer than that of 2.5 years typical for cars. Moreover, the aviation industry is more meticulous in critically appraising any new technologies, since its safety issues are under the spotlight right across the globe and they are strictly regulated by governments. Moreover, field tests also prolong the deployment cycle, since it is a challenge to organize dozens of aircraft for evaluation in a real-word scenario and it is also difficult to get permission to carry out evaluations on passenger flights due to the safety of life. Hence, joint efforts are necessary from both the academic and industrial communities for developing and sharing testbeds and for ensuring the security of AANETs in order to meet the critical market entry requirements of the aviation industry.

XI. CONCLUSION

The emerging demands imposed by the ever-increasing air traffic and by the desire to enhance the passengers' in-flight entertainment have stimulated the research efforts of both the academic and of the industrial communities, invested in developing aeronautical communications. AANETs may be expected to meet the demands of future aeronautical communications. However, the specific characteristics, applications, requirements, and challenges of AANETs have not been comprehensively reviewed in the open literature.

In this paper, we have characterized the scenarios, applications, requirements, and challenges of AANETs. We have discussed both existing and emerging aircraft communications systems designed for A2G, A2A, and A2S communications as well as in-cabin communications. The research community's efforts devoted to developing AANETs have been reviewed in this survey. A general design framework for AANETs, as well as key technical issues, is presented. Moreover, we outline a range of performance metrics as well as a number of representative multiobjective optimization algorithms for designing AANETs. Finally, some open issues of implementing AANETs in practical aeronautical systems have also been discussed.

It can be expected that, in the near future, the promises of AANETs will motivate further research efforts, which will benefit not only aviation but also the more general area of wireless *ad hoc* networking. AANETs will merge the self-organization of multihop *ad hoc* networks as well as the reliability and robustness of infrastructure-based networks, generating hybrid networking solutions applicable to miscellaneous applications in aircraft communications. ■

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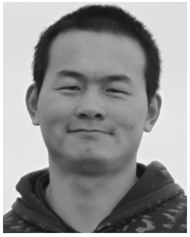

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