Advancing the Standards for Unmanned Air System Communications, Navigation and Surveillance

Denise S. Ponchak
NASA Glenn Research Center
21000 Brookpark Rd. MS 54-1
Cleveland, OH 44135
denise.s.ponchak@nasa.gov

Fred L. Templin
The Boeing Company
P.O. Box 3707 MC 42-59
Seattle, WA 98124
Phone: 425-373-2829
fred.l.templin@boeing.com

Greg Sheffield
The Boeing Company
P.O. Box 516 MC S064-2374
St Louis, MO 63166-0516
Phone: 314-302-7543
greg.l.sheffield@boeing.com

Pedro Taboso
The Boeing Company
Avenida Sur del Aeropuerto de Barajas, 38
28042 - Madrid; Spain
Phone: +34 91 768 8451
pedro.tabosoballesteros@boeing.com

Raj Jain
Washington University in St. Louis
Saint Louis, MO 63130
Phone: +1 314-322-8092
jain@acm.org

***Abstract*—Under NASA program NNA16BD84C, new architectures were identified and developed for supporting reliable and secure Communications, Navigation and Surveillance (CNS) needs for Unmanned Air Systems (UAS) operating in both controlled and uncontrolled airspace. An analysis of architectures for the two categories of airspace and an implementation technology readiness analysis were performed. These studies produced NASA reports that have been made available in the public domain and have been briefed in previous conferences. We now consider how the products of the study are influencing emerging directions in the aviation standards communities.**

The International Civil Aviation Organization (ICAO) Communications Panel (CP), Working Group I (WG-I) is currently developing a communications network architecture known as the Aeronautical Telecommunications Network with Internet Protocol Services (ATN/IPS). The target use case for this service is secure and reliable Air Traffic Management (ATM) for manned aircraft operating in controlled airspace. However, the work is more and more also considering the emerging class of airspace users known as Remotely Piloted Aircraft Systems (RPAS), which refers to certain UAS classes.

In addition, two Special Committees (SCs) in the Radio Technical Commission for Aeronautics (RTCA) are developing Minimum Aviation System Performance Standards (MASPS) and Minimum Operational Performance Standards (MOPS) for UAS. RTCA SC-223 is investigating an Internet Protocol Suite (IPS) and AeroMACS aviation data link for interoperable (INTEROP) UAS communications. Meanwhile, RTCA SC-228 is working to develop Detect And Avoid (DAA) equipment and a Command and Control (C2) Data Link MOPS establishing L-Band and C-Band solutions. These RTCA Special Committees along with ICAO CP WG/I are therefore overlapping in terms of the Communication, Navigation and Surveillance (CNS) alternatives they are seeking to provide for an integrated manned- and unmanned air traffic management service as well as remote pilot command and control.

This paper presents UAS CNS architecture concepts developed under the NASA program that apply to all three of the aforementioned committees. It discusses the similarities and differences in the problem spaces under consideration in each committee, and considers the application of a common set of CNS alternatives that can be widely applied. As the works of these committees progress, it is clear that the overlap will need to be addressed to ensure a consistent and safe framework for worldwide aviation. In this study, we discuss similarities and differences in the various operational models and show how the CNS architectures developed under the NASA program apply.

TABLE OF CONTENTS

1. INTRODUCTION

NASA Contract NNA16BD84C was an NRA program with a period of performance from August 17, 2016 through March 17, 2018. The goal of the program was to develop "revolutionary and Advanced universal, reliable, always available, cyber secure and affordable Communication, Navigation, Surveillance (CNS) Options for all altitudes of Unmanned Air System (UAS) operations." UAS CNS

eprint
IEEE Aerospace Conference, Big Sky, Montana, Mar 2-9, 2019

options apply to the operation of large UAS in controlled airspace and small UAS in uncontrolled airspace. This program resulted in several ideas documented in our previous papers [11-15].

In the case of controlled airspace, UAS must operate in harmony with manned aviation in the global Air Traffic Management (ATM) service. This means that Air Traffic Controllers (ATCs) and Airline Operations Controllers (AOC) must coordinate with the UAS remote pilot, who in turn directs the Unmanned Aircraft (UA) itself. This model may itself evolve as UAs incorporate ever greater levels of autonomy.

In the case of uncontrolled airspace, there will soon be millions of small UAS (sUAS) operating in the 200'-400' altitudes outside of ATM control. The sUAS will fall under the jurisdiction of the Unmanned (Air) Traffic Management (UTM) service, which is expected to be an automated form of traffic management service facilitated by UAS Service Suppliers (USS). The operating model will be a "Management By Exception (MBE)" principle where controllers and/or law enforcement agents engage only when anomalous and/or unlawful conditions arise.

New navigation and surveillance architectures must also be considered for safe operations of UAS in all altitudes. Additional navigation sources must be considered to augment the Global Positioning Satellite (GPS) service in the case of GPS degraded or denied environments. New surveillance systems must further be employed to augment Automatic Dependent Surveillance-Broadcast (ADS/B) from a security and scalability standpoint.

In the following section, we present an overview of the communication networks, communication data links, navigation and surveillance options considered or developed in our project. The document then concludes with a discussion of standardization activities.

2. OVERVIEW

Communications Networks

The global Air Traffic Management (ATM) system is evolving from an analog voice-only service (i.e., push-to-talk) to one where data communications capabilities for command and control (C2) are emerging to augment the traditional services. The International Civil Aviation Organization (ICAO) is therefore developing a new data communications architecture known as the Aeronautical Telecommunications Network with Internet Protocol Services (ATN/IPS) [1]. With the advent of UAS in the controlled and uncontrolled airspace, data communications will more and more replace analog voice especially with increasing levels of autonomy. Furthermore, data communications will need to be conducted in a "Beyond (Radio) Line of Sight (BLOS)" fashion where the parties of the communication are separated by multiple data link hops. The model, therefore, beings to resemble the manner in which the Internet conveys data units known as "packets" from a source to a destination over multiple links connected by routers.

In this Internet-in-the-sky scenario, the first-hop link (or a sequence of links) conveys data from the air to the ground where it becomes subject for forwarding over the ground-based Internetwork. However, several factors challenge the way normal Internet-style routing is conducted. First, UAS are mobile and can change communications network attachment points rapidly. These mobility events are known to cause stability issues for standard Internet routing protocols such as the Border Gateway Protocol (BGP) and Open Shortest Path First (OSPF). Second, UAS typically have multiple data link technologies, e.g., satellite links, cellular links, Wi-Fi links, etc., where the links may only be available during certain phases of flight and may even exhibit variable performance characteristics within each flight phase. The coordination of these multiple data links, therefore, becomes challenging from an Internetworking perspective. Third, the cost of operating individual data links must be considered. Similar to the way cellphones prefer Wi-Fi over cellular due to the data usage charges for the latter, the UAS must select the most cost-effective service for a given phase of flight.

These considerations become even more important for small UAS operating in uncontrolled airspace in the Unmanned (Air) Traffic Management (UTM) service [2]. There, in addition to the same mobility and multilink considerations as for ATM, the data link equipage size, weight, and power (SWAP) must be considered. The UTM service also differs from ATM in that it must by its nature be an automated system of UAS Service Suppliers (USS) rather than one that is continually monitored by Air Traffic Controllers (ATCs) and Airline Operation Controllers (AOCs).

For both the ATM and UTM, the systems must be designed from the beginning to support large and growing numbers of air vehicles. This means that each UAS must be assigned a unique Internet Protocol address or prefix so that routing can direct packets to and from the correct UAS. Since the current global Internet Protocol, version 4 (IPv4) service has run out of addresses; this can only be accommodated by adopting Internet Protocol, version 6 (IPv6). Furthermore, since standard Internet routing services including BGP and OSPF are not equipped to manage large numbers of highly mobile nodes, a new mobility-capable routing service is needed. A nominal mobile routing architecture known as Asymmetric Extended Route Optimization (AERO) [3] was developed under our project.

Finally, both small and large UAS must have some way of communicating with each other when no ground supporting infrastructure is available. This capability is provided by vehicle-to-vehicle communications data links where UAs that are within communications range of one another can exchange data packets independent of any infrastructure. This peer-to-peer communications capability can be leveraged to extend the data communications service so that safe operations can be maintained as UAS begin to incorporate more and more levels of autonomy.

Communications Data Links

In terms of data links, we investigated technologies developed for both controlled and uncontrolled airspaces. For controlled airspace, we examine satellite links, L-DACS, AeroMACs, along with the work being done in RTCA Special Committee 228 (SC-228) [4][5]. For uncontrolled airspace, we consider Wi-Fi, ZigBee, Bluetooth, and 4G/5G cellular. We also propose five ideas for future UAS data link developments.

Satellite Links: Satellite links are currently used by almost all large UAs and manned aircraft in controlled airspaces. Over the ocean, these are the only data links available for communications. Two key problems with current satellite data links are: low data rate, and large weight of the receivers. The data rate per user is typically only a few kilobits per second originally designed to support a few voice channels. The antenna sizes required at the receivers are too large for use on small UAs (sUAs). The receiver antenna and electronics for satellite receivers need to be miniaturized so that its weight and size is acceptable for sUAs. The total data rates on satellite systems need to go up by one or two orders of magnitude. This can be done by increasing the number of satellites in a constellation, by using Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) constellations, and by using the latest communication technology. For example, the SpaceX Starlink service, although not planned specifically for the UA market, is being designed for 50 Gbps per satellite with a total capacity of 200 Tbps.

L-DACS: One version of L-Band Digital Aeronautical Communications System (L-DACS), called L-DACS1 is the leading candidate for adoption for data link for in-flight phase. It is designed as a higher data rate supplement for VHF Data link 2 (VDL2). It uses 960 MHz to 1165 MHz in the L-Band. These frequencies are 1/5th of those in C-Band used for AeroMACS. Therefore, these can reach much longer distances than C-Band technologies. It can be used by both the manned and unmanned aircraft. L-DACS uses a protected band, which is excellent for a small number of aircraft. However, the number of sUAs is expected to be in millions and what is needed is a technology that operates in a license-exempt band and requires no coordination among multiple users using the same band. Therefore, while L-DACS may be used by large UAs, another data link is required for sUAs.

AeroMACS: Aeronautical Mobile Airport Communication System (AeroMACS) is the data Link designed by RTCA Special Committee 223 (RTCA SC-223) for ground communication at the airports [6]. Each AeroMACS base station covers a cell of 3 km radius. AeroMACS uses frequencies in 5.091-5.150 GHz (C-Band) that have been reserved for aviation. The spectrum band is protected and is, therefore, not a license-exempt band. Therefore, like most other service provider technologies, the channels cannot be shared by multiple service providers on the same location at the same time. It can be used at the airport for any communication. Therefore, it cannot be used off-airport by pilots trying to communicate directly with their UAs without an intermediary service provider.

Wi-Fi: Wi-Fi and its variants are the most commonly used data links for sUAs. The key advantage of Wi-Fi is that its cost is low and the design has matured. It operates in the license-exempt bands, and so it can be used by multiple competing users in the same space at the same time. Another advantage of Wi-Fi is that it is implemented in all smart phones and, therefore, if a Wi-Fi data link is used, smart phones can be used as controllers reducing the cost of the equipment. The key limitation of Wi-Fi is its short reach of a few km. The reach is extended by manufacturers by using proprietary modifications. As a result, there is no interoperability between UAs from different manufacturers. It would be desirable for NASA or FAA to set some interoperability requirements so that enforcement personnel can take control of UAs when necessary.

ZigBee: ZigBee runs at 900 MHz band and therefore can reach longer distances than Wi-Fi. It is also low cost and is, therefore, a protocol of choice for sUAs. In fact, most hobbyists, who build their own UAs use variants of Zigbee, called XBee and XBee Pro, 3DR, and RFD900. Since these are proprietary, there is no interoperability. It would be good if the market can reach a consensus and some interoperability tests can be conducted.

Bluetooth: Bluetooth's key limitation is its limited range of about 30 m. This short distance is sufficient for some applications, such as "Follow me" and swarms. In "follow me" applications, the UA follows the other end of the Bluetooth link, which is usually a smart phone. In the swarm application, a number of UASs flying together can exchange information with each other using Bluetooth. It is extremely low cost and small. It can be easily incorporated as a 2nd data link in addition to Wi-Fi or ZigBee. It uses a license-exempt 2.4 GHz band. Bluetooth chips are widely available, and so it is widely implemented in all smartphones and several sUAs.

Cellular 4G/5G: Qualcomm and several telecom carriers have conducted trials with drones and have shown the feasibility and applicability of their technology for UAs. Unfortunately, cellular technology is implemented only mostly along the highways and only near populated areas. The cellular signal in remote areas is non-existent or weak. So the UAs using cellular signal will have to follow the highways and not in a straight line between the source and destination. Another problem is that cellular infrastructure is designed and optimized for ground communications. Cellular signals have lobes pointing towards the ground. So the signal reaching skywards is less. However, it is compensated partly by the absence of interference in the skyward direction. The UAs using cellular will have to be designed with autonomous navigation so that they can operate autonomously in-between cell towers and sync up with the pilot when they reach the next tower.

Ideas for Future Work on UAS Data Links:

We have identified five ideas for future work as follows.

1. Commercial Non-Aeronautical Satellites: Aeronautical Satellites are currently limited by the available spectrum. Frequency bands and size must be agreed globally in ICAO, which is a long and slow process. While the process worked for manned aircrafts due to their limited growth rates, unmanned aircrafts are growing at rates several orders of magnitude faster. The growth can be sustained if non-aeronautical commercial satellite systems are allowed at least in the national airspace. An example is the SpaceX Starlink LEO constellation. It plans to offer a latency of 20 ms. With 50 Gbps per satellite, the total throughput with 4000 LEO satellites could be over 200 Tbps. Assuming 50 million customers, the throughput per customer will be 4 Mbps. This should be ideal for UAS communication.

2. Spiral Approach to Data Link Development: Currently, UAS data link development is not keeping up with the growth rates expected for the UAS deployment. AeroMACS and L-DACS1 are the only aviation-specific data links in development. Both use technologies that are now 10 years old. NASA and FAA should develop a generation plan similar to that used by cellular providers so that while one generation is being deployed the specs and design for the next generation are being set. If cellular technology is any guide, these generations should be 5-10 year apart. The key metrics for UAS data links are peak data rate, per user data rates, availability, and energy efficiency. We believe that an order of magnitude increase in total data rate would be a reasonable goal for the next generation. Some of this increase will come from increased spectrum that is being discussed in various international standards bodies. The remaining increase will have to come from increased spectral efficiency.

3. Enhanced Spectral Efficiency: Both of the aeronautical data links currently being developed, AeroMACS and L-DACS1, use OFDM. OFDM is now known to have several problems that limit its spectral efficiency in terms of bits/Hz. In order to guarantee orthogonality, each subcarrier should have a zero power at the neighboring subcarriers. This results in a power ripple and there is a significant spectrum overflow beyond the spectrum used by the subcarriers. This is overcome in OFDM by having an unused frequency band called guard band. Also, OFDM requires that all subcarriers be equally spaced. All subcarriers need to use the same symbol size and cyclic prefix and all users should time synchronize in the uplink otherwise they will interfere with each other. Newer technologies that overcome these problems are now being proposed in the literature and need to be applied for the next generation of UAS data links.

4. Adopt IoT Data Links: Internet of Things (IoT) market growth has resulted in development of several new data links which can be easily adopted for sUAS. These data links have much longer reach than current Wi-Fi and use license-exempt bands allowing their use in billions of IoT devices. The size, weight and power (SWAP) of IoT devices is similar to that of sUAs. Therefore, these technologies can be used for sUAS with little or no modifications. IEEE 802.11ah, also called long-range Wi-Fi or Wi-Fi HaLow, is an example of the IoT data link. It uses 700-900 MHz band and can reach many times longer than standard Wi-Fi which runs at 2.4 and 5.8 GHz. Wi-Fi Hallow has been designed with an energy efficient MAC which makes it useful for sUAS applications.

5. Adapt Vehicular Area Networks for UAS: Vehicular area networks (VANETS) are being designed for automobiles. UAS applications, in which VANETs can help include collision avoidance, emergency-alert broadcasts and geocasts. Geocast is a broadcast that is limited to a certain distance and can be used for geo-fencing to keep sUAs away from sensitive and prohibited areas. Unfortunately, UASs have SWAP limitations which are stricter than autos. sUASs have lower power, larger speed, smaller size, and need to cover longer distances than autos. Therefore, there is a need to adapt or make suitable changes to VANET protocols. DSRC (Dedicated Short Range Communications) is a VANET protocol developed by IEEE. While a frequency band in 5 GHz range has been allocated for DSRC and all cars are required to have it by 2020, there is little activity in terms deployment of ground infrastructure. The cellular industry, has therefore, developed its own VANET, called "Cellular Vehicle-to-X (C-V2X)" that uses the existing cellular towers. However, it still needs to get permission to use DSRC spectrum for vehicle-to-vehicle communications.

NAVIGATION

Regardless of Unmanned Aerial Systems (UAS) size and mission, all UASs share the need for navigation accuracy supporting guidance and control within a given airspace (e.g., Class A – G). In addition, the navigation accuracy serves as an input reference for various surveillance systems which may be fusing multiple sensor sources to support detect and avoid capabilities. Navigation accuracy supporting sensor fusing directly impacts the level of distortion for sensor processing, exploitation, and dissemination results. Distortion is translated to a level of uncertainty which will determine the number of UASs and Manned Aerial Systems able to fly within a given airspace region (i.e., air vehicles per square mile, aircraft horizontal & vertical separation/spacing per airspace class).

Ground-controlled and autonomous operations of UASs require continuous and accurate measurements of the vehicle's position, velocity, and attitude (orientation). Existing commercially available UAS ground station controllers rely on GPS for determining position and velocity, plus determine attitude using a GPS aided Inertial

Navigation Systems (INS). This means that existing ground station controllers will have difficulty navigating, guiding, and controlling UASs when GPS is unavailable.

UAS operating within controlled airspace will be required to maintain navigation equivalent to existing manned aerial systems, which is primarily supported by GPS. To allow UAS to operate within controlled airspace, a certified navigation source will be required on all UAS to ensure accuracy of location being reported to both UAS Traffic Management (UTM) and Aircraft Traffic Management (ATM) systems.

The most challenging airspace for a UAS is operating within uncontrolled Class G airspace. Existing Class G aerial systems are not required to have communications; they use VFR visibility requirements in class G airspace of 1 mile (1.6 km) by day, and 3 miles (5 km) by night, for altitudes below 10,000 feet (3,050 m) MSL but above 1,200 feet AGL. Beginning at 10,000 feet MSL, 5 miles (8 km) of visibility is required, day and night. Cloud clearance requirements are to maintain an altitude that is 500 feet below, 1,000 feet above, 2,000 feet horizontal; at or above 10,000 feet. MSL, they are 1,000 feet below, 1,000 feet above, and 1 mile laterally. By day at 1,200 feet (370 m) AGL and below, aircraft must remain clear of clouds, and there is no minimum lateral distance.

UAS navigating within uncontrolled airspace should be at least GPS-like accuracy for areas of operation with the confidence of avoiding terrain and non-cooperative objects. UAS will require better than GPS-like accuracy when operations need to be closer to the terrain, spacing tighter between aerial vehicles, and for quicker response to non-cooperative object detection and avoidance. Overall, UAS navigation requirements are driven by the safety of flight and mission needs for all classes of airspace operations.

In summary, the onboard UAS navigation architecture concept for both controlled and uncontrolled airspace operations within the report is approached by leveraging multiple sources with a minimalistic addition of equipage with the consideration that “no one stand-alone technology” will augment GPS in all flight phases in Class A – G airspaces. The proposed architecture is envisioned to host functions beyond navigation, such as surveillance, communications, vehicle management, flight controls, maintenance, etc., with the use of the Integrated Modular Avionics (IMA) computing architecture based on ARINC 653. The UAS navigation architecture concept is also envisioned supporting navigation functions by leveraging sensors used for non-cooperative detect and avoid capabilities and signal characteristics from onboard communications systems.

SURVEILLANCE

CNS technologies dedicated to the upcoming UAS market are needed. New CNS technologies must solve the same problems as “traditional” CNS systems (avoid collisions and avoid traffic jams) but with much greater accuracy and scaling properties. UAS surveillance is an important tool in the ATM process. Improved UAS surveillance systems are required to safely manage increasing levels and complexity of air traffic. Accurate surveillance shall be used as the basis for UTM.

The aviation environment is extremely conservative. Certification and adoption processes are so strict that when a new technology is finally acquired, it is usually already obsolete. However, current surveillance systems are close to saturation and will not be able to cope with the expected increase in air traffic density due to the upcoming disruption of UAs.

On the other hand, according to current regulations, there are no specific requirements (in terms of entry, equipment, or pilot certificate) for Class G airspace. However, the expected sUAS paradigm for the upcoming years suggests that a series of surveillance systems will be needed in order to enable safe and efficient operations and to detect non-regulatory compliant ones.

As current surveillance systems are not able to cope with the expected scenario, a new series of independent and dependent surveillance systems have been analyzed during the project in order to provide a complete surveillance solution for controlled and uncontrolled airspaces. Such systems have been developed with the objective of maintaining and potentially improving current aeronautical safety and security criteria.

In terms of surveillance, the first step consisted of the analysis of surveillance needs. As a result of this analysis, we established a series of thirteen requirements to enable the integration of UAS missions within the controlled and uncontrolled airspace. These requirements cover safety, capacity, efficiency, security, integration, cooperative and non-cooperative surveillance, controlled and uncontrolled airspaces, centralized and autonomous operations mode, surveillance data flows, and performance issues.

The first step of the project presents requirements for an Automatic Dependent Surveillance over Internet Protocol (ADS-IP) system, which entails cooperative surveillance systems that are able to cope with the upcoming paradigm of UAS air traffic and to overcome the limitations of current surveillance systems for controlled airspace.

The next step considers the development of a new surveillance system to enable UAS operations within controlled airspaces: ADS-IP, a cooperative surveillance system. The main functionality of ADS-IP is to provide a system able to manage the surveillance data of UAs flying within a specific area. UAs must be able to broadcast surveillance data. The term broadcast here does not necessarily mean traditional RF broadcast, but rather refers to logical broadcast (information transmitted to all the actors who need it). While current surveillance systems rely on the use of RF-based channels ADS-IP makes use of an underlying IP-based communications network. The use of IP networks and communication protocols allow ADS-IP to overcome most of the limitations and vulnerabilities of current surveillance systems (such as ADS-B or SSR). In terms of surveillance, the system will transmit not only current position information but also additional data such as altitude, velocity, flight intent, autonomy, system health, etc. It also enables the implementation of additional functionalities (such as tracking services, dynamic exclusion/inclusion flight zones, or even anti-collision mechanisms and emergency interventions).

The third step of the project focused on solutions for small UAVs flying within uncontrolled airspaces. In terms of surveillance two analyses were carried out; one for non-cooperative surveillance solutions, and the second one for cooperative ones. While some commercial solutions are already available in the market for non-cooperative systems, there is a significant gap for cooperative surveillance ones. "Micro" ADS-IP (uADS-IP) has been defined as an additional cooperative surveillance system proposal. Conceptually, uADS-IP functionalities are very similar to traditional ADS-B but adapted to the operation mode expected by sUAS in class G airspace. As a dependent system, the UAS itself determines its position and broadcasts it so that other vehicles or systems on the ground can receive it and make a picture of the traffic within a determined airspace. The system presents some characteristics to make it able to cope with the sUA paradigm in uncontrolled airspaces such as lower power transmissions combined with transmission encoding techniques. With respect to the security dimension, an encryption layer is proposed. The proposal is based on a symmetric encryption for the broadcasted surveillance data through carriers such as DSRC.

In the final phase of the project, the surveillance systems proposals were analyzed in order to determine their technology readiness. In this implementation analysis, technologies were identified to support integrated flight testing and demonstration. Finally, a series of research plans were developed to provide a technology readiness level sufficient for implementation of such proposals in 3 – 5 years.

3. UAS CNS STANDARDIZATION

UAS communications networks and data link technologies are currently undergoing close consideration in several industry standards bodies. The International Civil Aviation Organization (ICAO) conducts the development of standards for the future Aeronautical Telecommunication Network with Internet Protocol Services (ATN/IPS). The ATN/IPS will be an all-IPv6 network that connects aircraft with ATC and AOC controllers. While intended for traditional manned aviation in its first iteration, the expectation is that the network will grow to support UAS and Remotely-Piloted Aircraft Systems (RPAS) soon thereafter. The network architecture will be documented in ICAO document 9896.

In the ATN/IPS standards community, AERO is under evaluation as a candidate technology for mobility, route optimization, multilink, Quality of Service (QoS) and Traffic Engineering (TE). Two other candidate alternatives under consideration include the Locator-Identifier Split Protocol (LISP) [7] and Mobile IPv6 (MIPv6) [8]. All three of the candidates support node mobility, for example, when a UAS changes between data link connections.

The mobility service makes it possible to preserve communication sessions across mobility events so that neither of the correspondents are aware that a movement has occurred. For all three alternatives, the mechanism that supports this session continuity is known as "encapsulation" (also known as "tunneling"), where a packet with a stable and unchanging IPv6 address is encapsulated within an outer IP header with addresses that may change from packet to packet. The tunnel therefore presents an always-connected and always-available abstraction regardless of the underlying data links used to support communications. The tunnel endpoint can either extend all the way to the UAS, or terminate within the network at a network element known as a proxy. Since tunneling adversely effects the limited bandwidths offered by aviation wireless data links, the latter arrangement is typically preferred. AERO and LISP support this proxy mode of operations, while MIPv6 requires tunneling across the aviation data links. This issue can be addressed when MIPv6 is used in conjunction with Proxy MIPv6 (PMIPv6).

The ICAO mobility solutions also must support multilink operation. When multiple communications data links are available, the solution must support the ability to harness the available links in order to map the correct traffic to the correct links based on factors such as bandwidth, delay, cost, stability, etc. For example, the mobility solution may choose to map motion video to a UAS SATCOM link while mapping short text command and control messaging to a lower-bandwidth terrestrial cellular service such as VHF or LDACS. The mapping is accomplished through a traffic classification service using a set of values known as Differentiated Service Code Points (DSCPs) to direct Quality of Service (QoS)-based data link selection. The process of mapping traffic is also known as Traffic Engineering (TE). All three of AERO, LISP and MIPv6 support QoS-based multilink TE.

In terms of route optimization, a side effect of using tunnels is that oftentimes the data communications path in the underlying terrestrial network is much longer than necessary. For example, data packets originating in New York could be routed to San Francisco in order to reach their final destination in Philadelphia. Although this "dogleg" route is not a matter of concern for performance in ground domain networks where data capacity is on the order of several Gigabits per second, the sub-optimal route involves expensive transitions across network critical infrastructure and data links. It is therefore highly desirable to re-route the network traffic directly from New York to Philadelphia without having to cross the continent. In their current proposals for ICAO WG-I, both AERO and LISP support this route optimization while (P)MIPv6 does not.

Finally, the mobility system requires a means for signaling correspondent nodes when a source node has moved. This signaling originates from a network service responsible for keeping track of all nodes in the network. Centralized mobility management (CMM) services realize this requirement by keeping all mobility state in a centralized server or servers. CMM arrangements do not scale well when there are larger numbers of nodes, e.g., when more and more UAS/RPAS nodes come into the network. As opposed to CMM services, Distributed Mobility Management (DMM) solutions spread the mobility responsibility between many smaller servers. Each of the DMM servers is therefore responsible for tracking the mobility of just a small subset of the total number of aircraft in the system. These DMM servers can also be deployed as lightweight virtual machines in the cloud instead of expensive router and server hardware. AERO is an example of a DMM mobility service, while LISP and MIPv6 are based on CMM.

ICAO is positioned to select among the mobility alternatives as they move closer to finalizing document 9896. A likely outcome of the effort, however, would be an adaptation of the best components of the three. For example, AERO leverages the time-proven Border Gateway Protocol (BGP) for orchestrating the DMM servers, and all three solution proposals have indicated value in incorporating BGP. Other aspects of the solutions proposals will be examined and incorporated as appropriate.

While ICAO continues to develop the ATN/IPS architecture, RTCA SC-223 tracks the developments there and considers the application of IPS specifically for UAS and RPAS. RTCA SC-223 is also responsible for the development of the AeroMACS data link standards needed for supporting ground-domain terminal and maneuvering area communications. RTCA further interacts with ICAO and RTCA SC-228 through representation of technologists who participate in all three venues.

Meanwhile, RTCA SC-228 is developing the MOPS and MASPS standards for UAS detect-and-avoid in Working Group 1 and command and control (C2) data link in Working Group 2. Working Group 2 develops L-Band and C-Band data link standards with C-Band seen as the likely frequency for UAS data links. As part of the MASPS and MOPS, an Internetworking appendix (appendix F) has been added to the main document body. In appendix F, it can be seen that the remote pilot station and UAS need to communicate across third-party data link service provider (DSP) networks. The remote pilot station registers with each third-party DSP network and injects a "service" address into the network routing system. The UAS/RPAS in turn connects to the DSP network and establishes a tunnel to the remote pilot service address. In this way, the DSP network provides a rendezvous service between the remote pilot and the UAS. If the UAS has multiple data links, the remote pilot registers with each of the corresponding DSP networks. The AERO and MIPv6 services have been documented for this application.

While the aviation community develops standards specific to manned and unmanned aviation, an industry standards community known as the Internet Engineering Task Force (IETF) [9] develops computer networking standards known as Requests for Comments (RFCs) for the global Internet and industry enterprise networking. These standards are intended to apply to general use cases worldwide, and not just the aviation-specific use case. The IETF is considering all three of MIPv6, LISP and AERO in the standards process for general-purpose use. The standards continue to emerge in parallel with the ICAO and RTCA efforts. For the purpose of achieving an IETF-sanctioned networking service for aviation, the IETF has selected "A Simple BGP-based Mobile Routing System for the Aeronautical Telecommunications Network" [10] as a routing working group document with intention to publish as an RFC.

4. SUMMARY

The aviation industry is investigating Communications, Navigation and Surveillance (CNS) technologies to meet the expected demand of future manned and unmanned air system operations. These technologies will need to emerge within the 3-5 year timeframe in order to support this new data-oriented paradigm instead of relying on legacy voice. We have seen that communications-networks, communications-data links, navigation and surveillance technologies are already emerging at high Technology Readiness Levels (TRLs) while the standards bodies are working to select among one or more candidates in each area. The end-state goal is to support an effective CNS service for both manned and unmanned aviation in all classes of airspace.

ACKNOWLEDGEMENTS

The authors thank NASA for supporting this work under contract NNA16BD84C.

REFERENCES

[1] "ICAO 9896 Manual on the Aeronautical Telecommunication Network (ATN) Using Internet Protocol Suite (IPS) Standards and Protocols", Second Edition 2015.

[2] Kopardekar, P., et al., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations", AIAA Aviation Technology, Integration, and Operations Conference, June 2016.

[3] Templin, F. “Asymmetric Extended Route Optimization (AERO)”, draft-templin-intarea-6706bis, (work-in-progress), September 2018.

[4] RTCA SC-228, Operational Services and Environmental Definition (OSED) for Unmanned Aircraft Systems (UAS), DO-320, 2010, 236 pp.

[5] RTCA SC-228, UAS Command and Control (C2) Data Link White Paper, WP-2_C2, 2014, 88 pp.

[6] RTCA SC-223, Internet Protocol Suite (IPS) and AeroMACS, https://www.rtca.org/content/sc-223, October 2018.

[7] Farinacci, D., “Locator-Identifier Split Protocol (LISP”, IETF RFC6830, https://www.rfc-editor.org/info/rfc6830, January 2013.

[8] Perkins, C., “Mobility Support in IPv6”, IETF RFC6275, https://www.rfc-editor.org/info/rfc6275, July 2011.

[9] Internet Engineering Task Force (IETF) Request for Comments (RFC) Document Series, https://www.ietf.org/.

[10] Templin, F., “A Simple BGP-based Mobile Routing System for the Aeronautical Telecommunication Network”, https://datatracker.ietf.org/doc/draft-ietf-rtgwg-atn-bgp, August 2018.

[11] D. Ponchak, F. Templin, G. Sheffield, P. Taboso-Ballesteros, and R. Jain, "An Implementation Analysis of Communications, Navigation, and Surveillance (CNS) Technologies for Unmanned Air Systems (UAS)," 2018 Digital Avionics System Conference (DASC), London, England, September 2018, 10pp.

[12] D. Ponchak, F. Templin, G. Sheffield, P. Taboso-Ballesteros, and R. Jain, "Reliable and Secure Surveillance, Communications and Navigation (RSCAN) for Unmanned Air Systems (UAS) in Controlled Airspace," 2018 IEEE Aerospace Conference, Big Sky, MT., 13 pp.

[13] D. Ponchak, F. Templin, R. Jain, G. Sheffield, and P. Taboso, "UAS CNS Architectures for Uncontrolled Airspace," 2018 Integrated Communications, Navigation, Surveillance Conference (ICNS), Herndon, VA, April 2018, pp. 1-35

[14] F. Templin, R. Jain, G. Sheffield, P. Taboso-Ballesteros, and D. Ponchak, "Considerations for an Integrated UAS CNS Architecture," 2017 Integrated Communications Navigation and Surveillance (ICNS) Conference, Washington D. C., 11 pp.

[15] F. Templin, R. Jain, G. Sheffield, P. Taboso-Ballesteros, and D. Ponchak, "Requirements for an Integrated UAS CNS Architecture," 2017 Integrated Communications Navigation and Surveillance (ICNS) Conference, Washington D. C., 11 pp.

BIOGRAPHY

***Denise S. Ponchak** is Branch Chief of the Communications Architectures, Networks and Systems Branch at the National Aeronautics and Space Administration's (NASA) Glenn Research Center at Lewis Field in Cleveland, Ohio. The Branch is responsible for designing advanced networking concepts, architectures, and technologies for aeronautics and space applications. Prior to becoming Branch Chief, Ms. Ponchak was an Aeronautical Communications Project Manager focusing on increasing the National Airspace System's telecommunications capability, and a Communications Research Engineer supporting future satellite-based communications. She holds a Bachelor's of Electrical Engineering and a Master's of Science in Electrical Engineering from Cleveland State University in 1983 and 1988 respectively.*

***Fred Templin** is a computer networking R&D professional with a focus on Internet protocol and data link specifications, operating system networking internals, networked applications, and networked platforms. He has in-depth experience in Internet networking and security architectures for unmanned air systems, civil aviation, tactical military, space-based systems and enterprise network applications. Mr. Templin has been an active contributor to the Internet Engineering Task Force (IETF) since 1999. He is currently a senior research engineer in Boeing Research & Technology (BR&T) since May 2005, where he is an Associate Technical Fellow of The Boeing Company.*

***Greg L. Sheffield** is a Senior Research Engineer in the Boeing Research & technology (BR&T) Avionics Systems Technology group. Greg's experience includes over 26 years working with commercial and defense communications, navigation, and surveillance technologies and products. He has contributed to a number of IEEE, RTCA, ARINC, and SAE standards. Most noted is his contributions related to digital communications using ACARS, second-generation TCAS combined with ADS-B, Navigation solutions in denied or degraded environments, and affordable open avionics architectures solutions. Greg is a retired Navy Flight Officer and holds BSEE, BSCS, SysEngMS, and MBA degrees. He lives and works in the St Louis, MO area.*

***Pedro Taboso** is a Telecommunication Engineer (5 year-degree, Polytechnic University of Madrid) with a background in IT systems and a proven professional and hands-on experience within Cyber Defence and Information Assurance fields. Pedro holds relevant security trainings and certifications such as CISA (Certified Information Security Auditor), ITILv3 and SANS 508 (Computer Forensics). He has a strong background on Information Security projects (penetration testing, ethical hacking, security architecture design, risk analysis…). During the last four years, he has been working on applications development for "Security- Over- CNS systems" projects, defining and developing new Surveillance systems for both manned and unmanned aircraft.*

***Raj Jain** is a Fellow of IEEE, ACM, and AAAS. He is a winner of 2017 ACM SIGCOMM Life-Time Achievement Award, 2015 A.A. Michelson Award. Dr. Jain is currently the Barbara J. and Jerome R. Cox, Jr., Professor of Computer Science and Engineering at Washington University in St. Louis. Previously, he was one of the Co-founders of Nayna Networks, Inc – a next-generation telecommunications systems company in San Jose, CA. He was a Senior Consulting Engineer at Digital Equipment Corporation in Littleton, Mass and then a professor of Computer and Information Sciences at Ohio State University in Columbus, Ohio.*