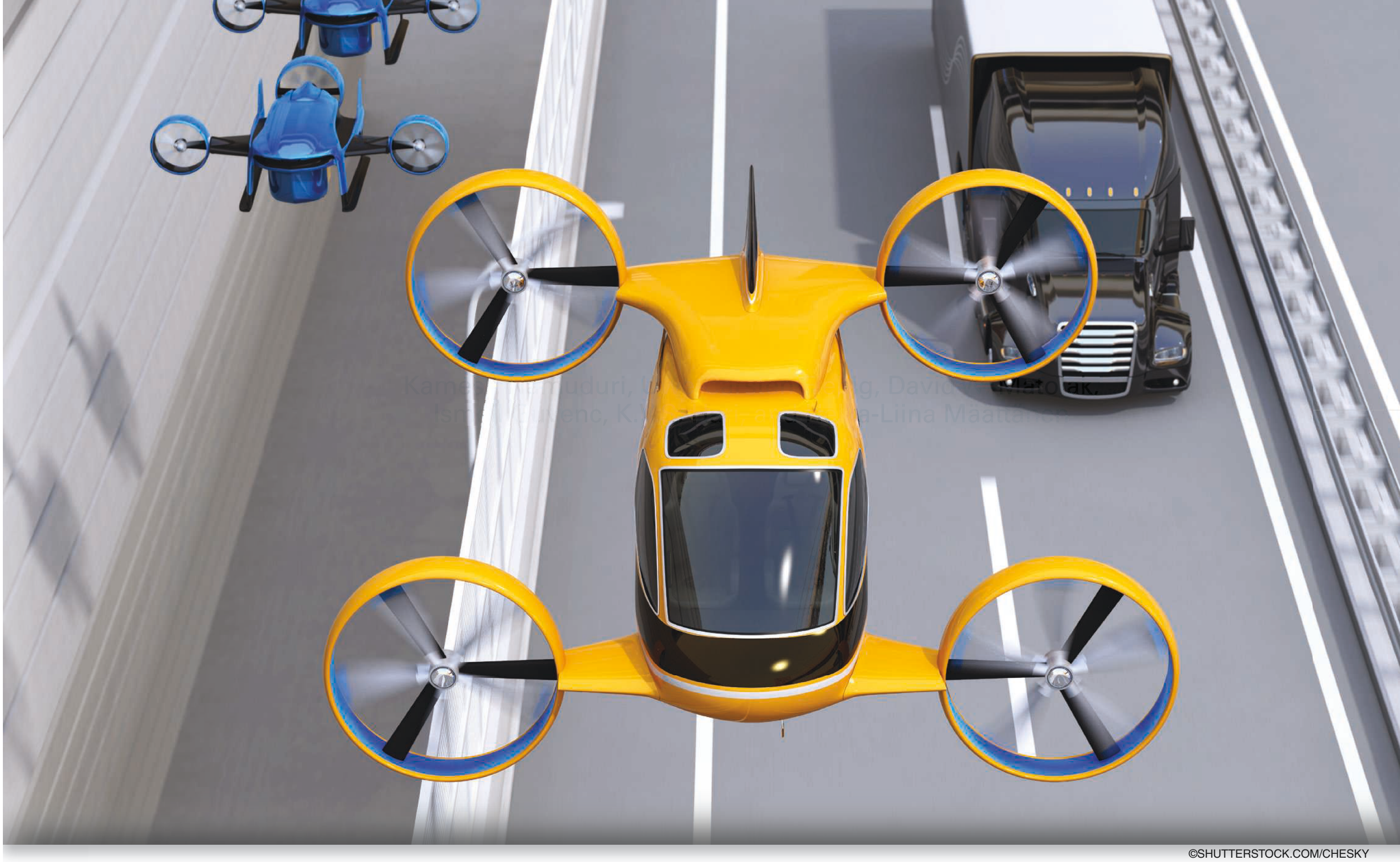

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ADVANCED AIR MOBILITY

Research Directions for Communications, Navigation, and Surveillance

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Advanced air mobility (AAM) is an emerging industry focus as well as a research and development discipline. Innovations and technologies resulting from AAM will change the way that we move cargo and people in and around cities. Industry is moving fast with excitement to deploy AAM solutions. However, there are multiple technical challenges that need to be overcome before AAM becomes a reality. This article takes a closer look at the technology readiness level of AAM solutions in the area of communications, navigation, and surveillance (CNS) and identifies open research problems as well as directions to address them. In particular, we discuss current approaches and future research challenges in air corridor design, air-to-air (AA) communications, 3rd Generation Partnership Project (3GPP) support for navigation, and detect and avoid (DAA)/collision avoidance, among other areas, for supporting future AAM operations.

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Background

AAM will add a new dimension of mobility to our lifestyle—the unmanned transportation of people and goods in and around cities [1]. Once AAM becomes a reality, hundreds or even thousands of unmanned aircraft systems (UASs) will be flying in our neighborhoods. Industry is moving with much enthusiasm, pushing aviation authorities to establish the rules of engagement. How far are we from AAM solutions, including air taxis and air ambulances? This article highlights several key research problems in the critical area of CNS and suggests ways to address them.

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AAM Architecture

Originally called *urban air mobility* (*UAM*), AAM (see Figure 1) is an evolution from its predecessor, the UAS traffic management system (UTM). While a UTM is designed for small UASs flying at or below 400 ft above ground level (AGL), AAM includes larger aircraft carrying people and/or cargo at altitudes between 500 and 2,000 ft AGL. AAM platforms include newer aircraft designs with vertical takeoff and landing capabilities.

A key subsystem in the AAM architecture [2] is the provider of services for UAM (PSU), which will provide services to support operations planning, flight intent sharing, strategic and tactical deconfliction, and airspace management functions. PSUs will exchange information with other PSUs via a network that enables safe, efficient operation within the AAM corridors—volumes of airspace dedicated to AAM use. Moreover, PSUs make use of discovery and synchronization services to identify active areas where other aircraft are flying as well as UAS volume restrictions (UVRs), representing areas that need to be avoided due to hazards or other types of restrictions, both permanent and temporary. The AAM architecture will also include supplementary data service providers, which provide services such as weather information, and a flight management information system, which is used to manage manned aviation. Specifications developed by ASTM International are being followed for data exchange protocols between one subsystem to another within the AAM system.

Contributions

Although there are several technical and societal barriers that need to be addressed before AAM services, such as air taxis and air ambulances, can be deployed for real-world applications, this article highlights some of the most critical CNS challenges to which academic researchers can contribute. These include:

- air corridors
- AA communications
- 3GPP support for navigation
- DAA/collision avoidance.

These topics are discussed in the "Air Corridors," "AA Communications," "3GPP Support for Navigation," and "DAA" sections. A few other areas of research, including navigation in GPS-denied environments, noise mitigation, and security and privacy, are briefly discussed in the "Other Related Research Topics in CNS" section. This list is not exhaustive, but it represents a critical subset of challenges. Although some of these problems may have equivalent solutions in terrestrial systems or manned aviation systems, they are not always directly portable to the AAM system.

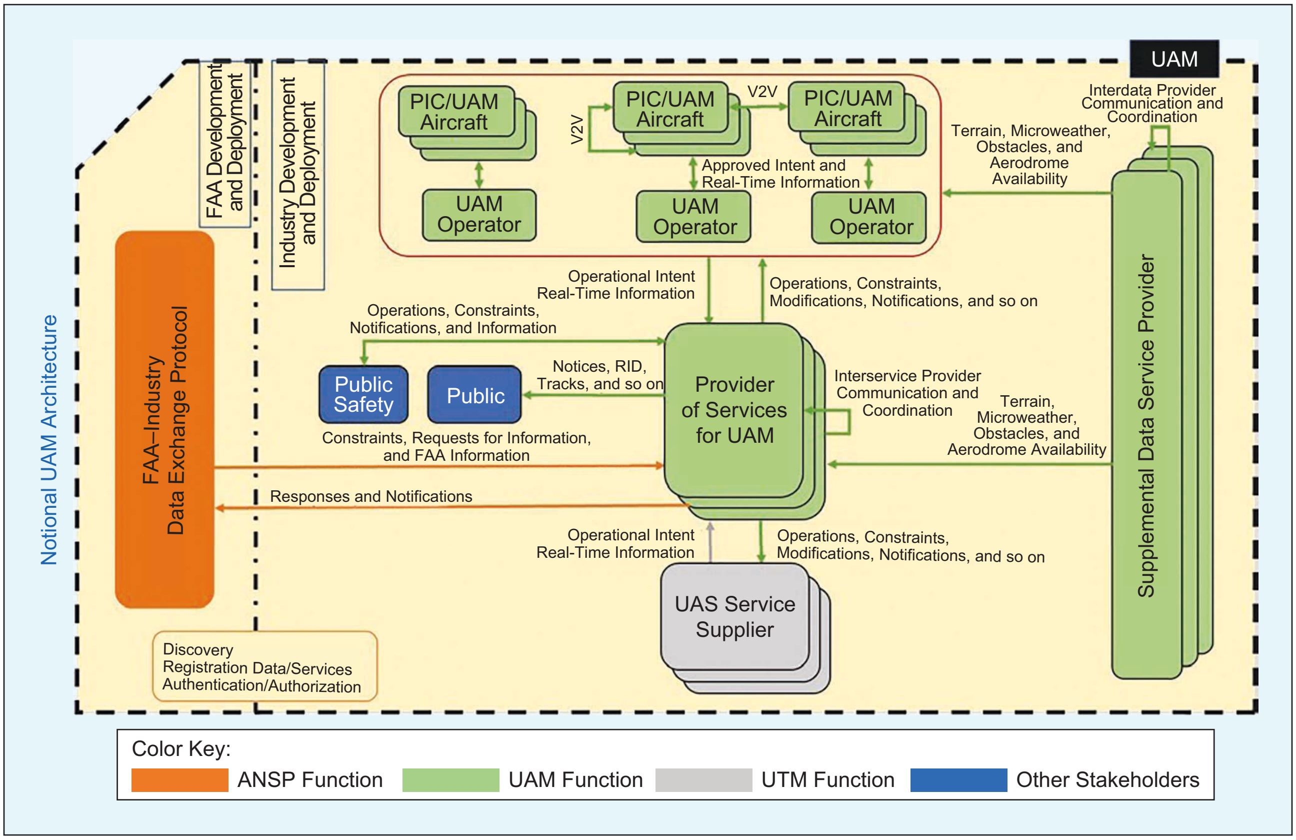

FIGURE 1 The AAM/UAM architecture. (Source: NASA; used with permission.) ANSP: air navigation service provider; PIC: person in command; RID: remote ID; V2V: vehicle to vehicle.

Glossary

There are several acronyms that this article refers to in the following sections. For convenience, most relevant terms are listed in Table 1.

Air Corridors

Air corridors are 3D volumes of airspace reserved for UASs for AAM traffic. Air corridor design specifications are specific to each country and are defined by the respective federal aviation authorities. In the United States, the Federal Aviation Administration (FAA) defines air corridors in class B, C, or D airspaces. The FAA also defines the expected performance requirements of any UAS flying in an air corridor.

The design of air corridors follows the overall goal of providing efficient and safe operation of UASs, respecting UVRs and environmental constraints. If only a few UASs are airborne within some volume, the control of UASs and their safe operation is relatively easy. However, as the number of UASs continues to grow, an appropriate air corridor concept has to be developed. This concept will set the rules for the choice of flight trajectories. At one extreme, trajectories may not be subject to any restrictions; an example is when UASs fly along the shortest path between takeoff and landing locations. At the other extreme, only predefined 3D flight routes are allowed; an example is when UASs must follow the layout of streets. Still, there are numerous open questions, and here we mention a few:

- Which air corridor concept is the safest one?
- Which requires the least amount of coordination for collision avoidance?
- Which provides the highest flexibility to cope with growing UAS traffic?
- Which guarantees the shortest flight times?
- Which allows for priority flights?
- Which can handle the bottleneck of locations where the rates of takeoffs and landings are extremely high (like at a distribution warehouse)?
- Which is most robust when hazards emerge?

A possible air corridor concept is illustrated in Figure 2 consisting of air corridors with three layers. This design is shown for visualization purposes only and is not approved or standardized. In this design, the top and bottom layers contain one-directional tracks, or skylanes. The middle layer contains intersections (“roundabouts”) for the AAM aircraft to change their direction of travel. For example, if a southbound UAS needs to turn east, it will descend from layer 1 to layer 2, take a quarter turn in the roundabout, descend to layer 3, merge into the eastbound skylane, and continue its travel. The designs of such air corridors, traffic rules in these air corridors, safety requirements, and performance specifications are still evolving. Air space design concepts, such as the geofence [3], are currently being considered by various research groups.

TABLE 1 ***A list of acronyms.***

Acronym	*Expansion*
3GPP	3rd Generation Partnership Project
5G	Fifth generation
AA	Air to air
AAM	Advance air mobility
AGL	Above ground level
AeroMACS	Aeronautical mobile airport communication system
ASTM	American Society for Testing and Materials
BS	Base station
CITS	Cellular intelligent transport systems
CNS	Communication, navigation, and surveillance
D2D	Device to device
DAA	Detect and avoid
DFRC	Dual-function radar communications
DLL	Data link layer
DSS	Discovery and synchronization service
FAA	Federal Aviation Authority
FIMS	Flight information management system
GCS	Ground control station
HO	Handover
LDACS	L-band digital aeronautical communications
LOS	Line of sight
LTE	Long-term evolution
MIMO	Multiple-input, multiple-output
MPC	Multipath component
NR	New Radio
PC5	Device-to-device interface
PHY	Physical link layer
PSU	Provider of service for urban air mobility
RCS	Rich communication services
RRC	Radio resource control
RRM	Radio resource management
SDSP	Supplementary data service provider
UAM	Urban air mobility
UAS	Unmanned aircraft system
UE	User equipment
URLLC	Ultrareliable low-latency communications
UTM	Unmanned aircraft system traffic management system
UVR	Unmanned aircraft system volume restriction
V2V	Vehicle-to-vehicle
VDL	Very-high-frequency digital link
VToL	Vertical takeoff and landing

There is a need to find a substitute or near equivalent for traffic lights in air corridors. The most obvious choice for this is AA vehicle-to-vehicle (V2V) communications among the UASs. [The term *V2V* has been used for approximately 15 years to mean automobile-to-automobile (car-to-car) links. Hence, we discourage its use for airborne vehicles.]

A simple use case for AA communications in air corridors is illustrated in Figure 3. This figure depicts a scenario in which normal flight operations are taking place in a skylane, and, suddenly, one of the vehicles detects an airspace hazard (an obstacle, such as a dense cloud). In this scenario, vehicle A, which detected the hazard, acts first. It needs to avoid the obstacle and share this information to the following vehicles, B and C, in real time. Further, depending on the estimated time that it takes for the airspace hazard to dissipate, information needs to be transferred to the ground control station to avoid potential congestion in the skylane. Standardization efforts for AA communication protocols, use cases, spectrum needs, and security requirements are currently taking place in the AAM community. The "AA Communications" section outlines the fundamental research needed for developing efficient V2V communication strategies.

AA communications can be combined with the principles of radar systems to develop dual-function radar communication (DFRC) systems [4] where radar waveforms can be designed to carry information to communicate with other vehicles in the vicinity. The dual use of DFRC for sensing and communications has potential applications in AAM, particularly in the CNS domain.

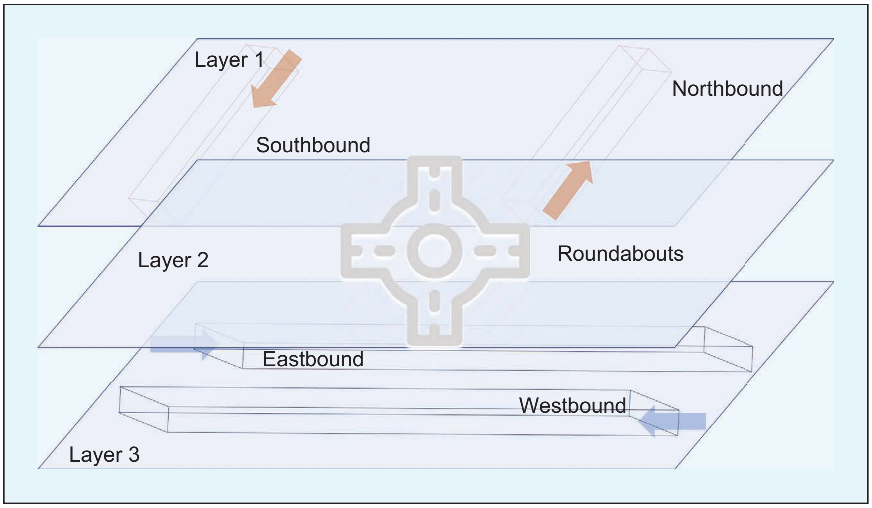

FIGURE 2 An air corridor.

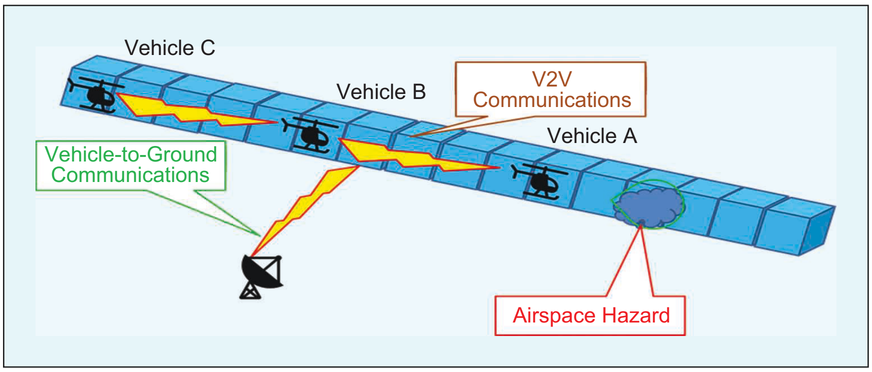

FIGURE 3 The need for V2V communications in air corridors: an example use case. (Courtesy: Unmanned Experts.)

AA Communications

AA communications, like air-to-ground (AG) communications, have a history nearly as long as aviation itself. As with terrestrial settings, multiple network topologies (e.g., mesh, relay, star, and so on) can be employed. A primary difference from terrestrial networks arises from high aircraft speeds: AA network topologies can change rapidly. Until air traffic densities become much larger than presently envisioned for AAM applications, AA communications will likely serve a supporting role to primary AG communication links, whereas navigation, and, in particular, surveillance, will rely more on AA signaling. Individual aircraft surveillance is usually termed *DAA*. For all three functions (CNS), reliability at the lower layers of the communications protocol stack is critical. Hence, in this section, we focus on AA signaling at the physical and data link layers.

When link distances are on the order of altitudes or smaller, the AA channel is very close to a free-space channel, assuming mostly azimuth-covering antennas. This is easily deduced from geometry and basic propagation principles. The primary obstacle that affects the AA channel is the Earth surface, and, as link distances increase, reflections from the Earth surface become the next significant channel component in addition to the line-of-sight (LOS) component [5]. For lower aircraft altitudes, the AA link range will decrease since the radio LOS over the curved Earth is proportional to the square root of the altitude. In addition, the probability of obstruction of the AA link increases as the altitude decreases.

In the best of circumstances, when aircraft are well above obstacles, one can approximate the AA channel as a pure free-space channel, with a propagation path loss proportional to the reciprocal of the square of the link distance d. Proximity to Earth and to Earth-based objects can substantially alter this first-order model. For links between aircraft that are not too close to the ground and are at approximately the same altitude, this $1/d^2$ free-space path loss model allows large link ranges in comparison to terrestrial settings, where, often, a $1/d^3$ or $1/d^4$ attenuation relation holds.

The simplest enhancement to the free-space channel model is to account for the presence of Earth. If link distances are short enough, a flat-Earth model may suffice; this will depend on the link geometry, aircraft altitude, and relative terrain roughness. Including an Earth-surface reflection makes this a two-ray channel, for which many good models exist [6].

At altitudes low enough to allow significant reflections from terrestrial obstacles, additional multipath components (MPCs) may be present. These can occur at relatively large values of delay and, with aircraft motion, will tend to be intermittent, as found for the AG channel [7].

In addition to the link geometry and environment, antenna characteristics are another primary factor affecting the physical layer of AA links. For example, a well-designed simple monopole antenna will have its antenna pattern changed—sometimes drastically—when mounted on an aircraft. Mounting location is also important since an antenna mounted on one side of the fuselage (e.g., the top) will typically suffer significant gain reduction if used to receive a signal coming from the direction of the other side of the fuselage (e.g., the bottom). Thus, multiple antennas distributed across the aircraft may be necessary if connectivity is truly required to be 3D.

Directional antennas suppress MPCs and can enable larger link ranges, but, in a dynamic AA setting, antenna pointing and tracking can be challenging. For AAM applications, some of the most challenging cases will be in the near-urban and urban environments. In the near-urban case, flights will likely follow established air corridors well above buildings; hence, AA channels may be well modeled by a two-ray channel, in which the terrain cover type will determine the strength and nature of the reflection (specular or diffuse). Work on estimating and validating these air corridor channel models should be done for the appropriate frequency bands.

For the urban case, additional MPCs will be present from buildings and other terrestrial structures (e.g., water tanks or highway overpasses) that will also sometimes act as obstructions. Obstruction attenuation generally increases with frequency. To date, largely because of the difficulty of conducting flight tests over and within urban areas, most channel models for this case rely solely on analyses and simulations. Thus, actual experimental work on this topic would be very valuable.

A first wideband measurement campaign, which aims at getting a deeper understanding of signal propagation in urban AA environments, was conducted in 2019 [8]. Various flight scenarios were assessed with the goal of measuring the propagation conditions in challenging scenarios: e.g., two drones flying one behind the other along building facades at a close distance to the building (see Figure 4), a drone landing in the inner courtyard of a building while another one flies around the building, and two drones flying on a potential collision course toward the corner of a building. Inherently, LOS as well as non-LOS situations have been assessed. The first findings reveal that the channel exhibits a large variety of propagation phenomena encompassing single, double, and triple reflections; diffraction; scattering; shadowing; and combinations. While evaluations are ongoing, the existing results already indicate that the AA channel for urban scenarios in which drones fly below rooftops is at least as complex as car-to-car channels.

A future research goal is to identify critical propagation scenarios like the occurrence of strong reflections potentially arising from large window facades or long-lasting shadowing. Those scenarios are crucial for DAA since they may either interrupt the AA communication link or result in an incorrect reception of messages. Although two potentially colliding drones may have many chances to receive respective messages from each other prior to the potential collision, it is important to understand the extent to which the propagation medium contributes to communication outages. Furthermore, there are events in which a collision course may occur unexpectedly, e.g., due to a mechanical failure or a sudden wind gust. Neighboring UASs have to rapidly and reliably receive information about such events. Therefore, a deep understanding about the channel conditions is essential.

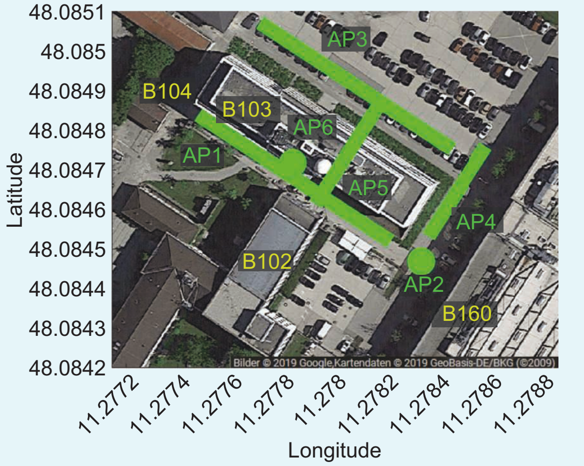

FIGURE 4 Some of the scenarios assessed in an AA propagation measurement campaign: two drones fly closely along the facade of building B103, one behind the other; one drones flies along the north side of building B103, while the other drone flies along its south side; and one drone is located at a balcony (AP6) of building B103, whereas the other drones flies over the rooftop of that building.

The actual signaling formats for AAM links will depend on applications. There may be some messages that have very stringent reliability requirements as well as latency requirements. The use of the cellular community's ultra-reliable low-latency communications is, hence, worthy of consideration for these cases. Otherwise, it is likely that AA links will employ the same signaling schemes as AG links. Contending schemes include 5G cellular; very-high-frequency digital link; L-band digital aeronautical communications; aeronautical mobile airport communication systems; and others, such as military systems (Link 16 and Common Data Link), and schemes still under development.

3GPP Support for Navigation

In release 15, 3GPP conducted a study to investigate the ability of the LTE network to provide connectivity for low-altitude UASs. The study defined performance requirements for both command and control as well as for UAS application data. From 3GPP's perspective, both categories are "user-plane" traffic. For command and control, the latency and bit error rate were concluded to be more important than the data rate, which is more crucial than application data, especially with a video use case. Further, channel models and typical scenarios were defined for studying the potential issues and potential solutions to be addressed later in the work item phase. The outcome of the study was documented in the 3GPP technical report [9], which also included field measurement results. In [10], the authors present a related study and findings of UAS operation in cellular networks.

The release 15 LTE work item [11] specified the key features identified during the study item phase to enhance UAS operation in cellular networks. One of these features is height reporting when a UAS crosses a height threshold. Multiple height thresholds can be configured for a UAS, e.g., 50, 100, and 250 m. The report includes the height, location (3D), and horizontal and vertical speeds. Another specified feature is reporting of the signal strength measured at the UAS when *N* neighboring base stations' (BSs') signal strengths are above a threshold. This, together with the height reporting, is used for both interference detection and flying mode detection. One key feature is core network signaling for subscription-based identification for the network to verify whether or not a mobile device can be served as a UAS in the network. Additionally, support for signaling flight path information from the UAS to the BS was added to the air interface signaling protocol. This includes network polling of list of waypoints (3D locations) and time stamps if available. These enhancements are described in more detail in chapter 6 in [12].

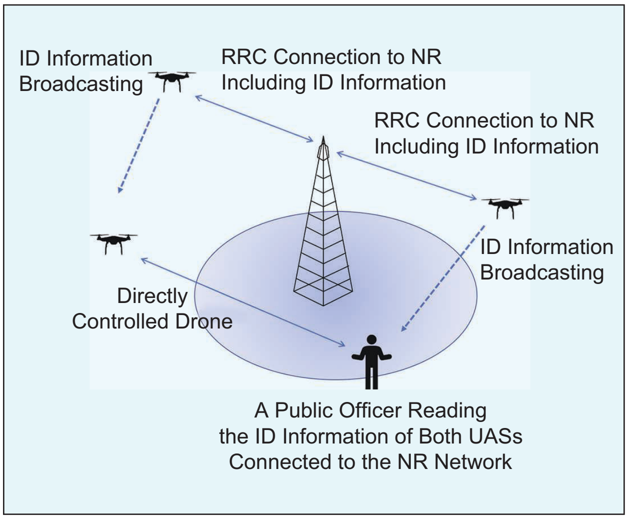

FIGURE 5 A network based on direct UAS identification. The two UASs are connected via Radio Resource Control (RRC), and the network is able to identify and locate the drones. Both drones are also configured to broadcast ID information, which may include both device ID and owner information. A local officer may read the ID information directly with a handheld device or use a drone to read the information.

Currently, 3GPP is preparing for release 18, which is planned to start in the second quarter of 2022. Specifying enhancements for UASs for 5G New Radio (NR) networks is one topic to be considered further, and the current consensus for the content is aligned with the work item proposal in [13]. The scope of the potential work item includes introducing corresponding support for 5G NR, as was specified for LTE; support for drone remote identification broadcasting over PC5; a device-to-device (D2D) interface; and, additionally, further enhancements for mobility and radio resource management.

The FAA has issued its ruling on UAS identification, and two methods are expected based on the class of drone. One is network tracking, where the location information of the UAS is conveyed back to a UAS service supplier. As the 5G NR already supports location reporting from a mobile device—a UAS in this case—to the network, there is no need for further 3GPP specification efforts to enable this identification method. Additionally, the height threshold-based height reporting may be configured to include the UAS location as well. Figure 5 depicts the UAS broadcasting ID information. The other method is UAS broadcast ID, where the device transmits its identification and owner information. Based on the class and usage of the drone, network-based or UAS ID broadcasting—or both—may be required.

For 5G NR and LTE to support the ID broadcasting, a specification effort is needed. 3GPP enables a D2D link, also defined as a *sidelink* or *PC5*, which is part of the cellular intelligent transport system. The PC5 link enables communication between other vehicular mobile devices or toward roadside units. This provides a framework for supporting UAS remote ID broadcasting. As an LTE BS may schedule 5G NR user equipment (UE), and 5G NR BS may schedule LTE UE, it has been agreed in release 18 to study and specify if the support for this feature is needed for both NR and LTE.

Additionally, the topic of collision avoidance has emerged during the release 18 discussions and is proposed to be addressed during the 3GPP normative work. The PC5 already supports broadcasting messages for collision avoidance over a sidelink, and the reuse of these traffic-safety messages should be the starting point. However, there may be additional enhancements that could benefit the specific UAS use case, such as sharing some information in flight paths.

The release 18 UAS discussions also include considering further enhancements for uplink beamforming and beam management to further control the interference and to improve the link quality with faster switching of uplink beams toward the BS. However, these suggestions need to be considered against the multiple-input, multiple-output release 17 enhancements, which may already provide the needed level of improvements.

To enable better mobility performance, there are proposals to use and enhance a so-called conditional handover (HO). In a regular HO, the mobile device starts connecting to the target cell immediately upon receiving the HO command. In the case of a conditional HO, the mobile device receives an HO command with a condition, and, when the condition is fulfilled, the device starts connecting to the target cell. Currently, the conditional HO command may include up to eight target cells and up to two conditions per target cell, and the conditions can be signal strength related only. For the UAS use case, additional conditions, such as the location or height, may be considered. These could be used independently or in combination with a signal strength-specific condition.

For example, the UAS performs an HO to cell A when the height is above a certain threshold and the signal strength is above a certain threshold. The same cell may be also configured separately with only a signal strength-specific threshold. The device receiving both of these configurations will evaluate both and trigger the HO based on which configuration in its conditions is first fulfilled. In this way, the device may be guided to perform the HO toward the cell at different signal strength conditions depending on whether it is flying or not flying. This may be useful, as, in a flying state, the free-space propagation becomes the dominant factor, and the coverage map of the cells differs from the ground situation.

DAA

DAA is one of the most crucial components in AAM. Due to the large number of UASs expected in the future, conventional DAA approaches will not work reliably any more with humans in the loop but will have to operate fully autonomously and have to be tailored to the air corridor concept (see the “Air Corridors” section.) Furthermore, when no planning of flight trajectories prior to takeoff against potential collision courses is carried out, the DAA mechanisms must be powerful, as their intervention is often required. However, even when flight trajectories are carefully planned in advance, many conflict situations can arise:

- High-priority flights may force UASs to change courses, to decelerate, or to stop for a moment and, in turn, the UAS has to react to these changes.
- Unforeseeable events, like strong wind gusts or mechanical failures, can cause collision courses, which have to be resolved in very short time.
- Flight corrections to avoid collisions, e.g., with birds, can result in further collision courses.

The DAA has two functions: “detect” aims to get awareness about potential collision courses, and “avoid” provides correction maneuvers for all conflicting UASs. “Detect” gets the required information over a communication link, be it AA communication or AG communication, as well as from local sensors, such as cameras, radars, and lidars. The communication messages contain information about the current position, current velocity vector, future waypoints, destination, and priority mode as well as about the size, volume, and freight type of a particular UAS. It is obvious that the communication link must be reliable and highly available, and an interruption of the link (due to reasons that may also include interference, jamming, and spoofing) may cause major safety problems. Further research on the robustness and availability of communication links considering a variety of hazards and appropriate countermeasures is very important.

Communication links have the advantage that they can be operated 24/7. For example, the recent remote ID rule making by the FAA [14] requires (through the standard remote ID-capable drone option, which is one of the three modes) that the drone broadcasts some critical information. Such information includes the drone’s unique ID, location and altitude, velocity, control station location and elevation, time mark, and emergency status. This broadcast message can be at a spectrum similar to what is used by Wi-Fi and Bluetooth, while the rule making does not specify or mandate a fixed frequency or technology. Such remote ID information, if it can be reliably, seamlessly, and continuously monitored, will be the primary source for DAA operations. Additional research is needed to compare the suitability of different wireless technologies for remote ID operations.

The RF signals between a drone and its controller can also be passively monitored for detecting, classifying, localizing, and tracking a drone [15]. This requires prior training of the system with signals from various commercial drones and their controllers. While various different machine learning algorithms are explored to improve the detection and classification accuracy, there is need to reduce detection and classification errors, especially at low signal-to-noise ratios. For improved tracking, there is further research needed to develop mobility models that consider typical operational environments and vehicle dynamics of typical drones and AAM vehicles.

Local sensors, like cameras, can be used complementarily to communication links but require good visibility conditions, a high visual resolution, and sufficient onboard computing power. Also, radar and lidar can complement or back up communication links. Radars can be used to not only detect and track the drones but also classify them using their measured radar cross section and additional micro-Doppler features [16]. There is further research needed for developing DAA mechanisms to distinguish birds from small drones, which can benefit from rich communication services and micro-Doppler-based features. Local sensors may have difficulties detecting small obstacles and small UASs from larger distances. The landing of UASs on rooftops could be an ultimate option when communication is jammed and other DAA modes are not effective.

When the DAA mechanisms identify that there is a collision course involving one or more UASs, centralized (the UAS action is communicated by a remote entity) or UAS-centric (each UAS takes its own decision) measures can be taken. When there are collision courses where more than two UASs are involved, there is a need to develop novel avoid concepts. These situations occur when UASs fly on air corridors one after the other: when an unmanned aerial vehicle (UAV) has to decelerate, it has an impact on all other UASs following the first one—similar to platooning on roads for self-driving vehicles. Correction courses may use the third dimension, causing UASs to use air layers where no UAS is expected to fly. However, if, in these air layers, other UASs are already present, new conflicts may arise. With only a few UASs in operation, this issue is not of great significance, but it will become crucial with a growing number of UASs. When collision avoidance maneuvers cause further conflicts, the overall stability of AAM is in danger.

Other Related Research Topics in CNS

In this section, a few other areas of future research are outlined, including navigation in GPS-denied environments, noise mitigation, and security and privacy.

Navigation in GPS-Denied Environments

A received GPS signal is critical for a UAS to estimate its own location in the airspace. Without knowing its own location at any given time, a UAS may not be able navigate to its next intended location. Potentially, a UAS may crash if the GPS signal is not available for more than a few seconds unless there is another means to accurately estimate its location. Although there are several alternatives based on cameras, inertial measurement units, and machine learning, such methods are not robust enough to substitute for GPS. A potential strategy may be a combination of such methods.

Noise Mitigation

Noise pollution is a major concern with UAS deployment in urban settings and is a barrier for community acceptance of AAM [1]. UASs may have radically different noise characteristics from those of traditional aircraft due to differences in size, weight, and the technologies used in propulsion and airframe design. Strategies for noise mitigation include surface texturing, among others. The lack of descriptive aircraft models causes uncertainty in the estimation of acoustic signals. Accurate 3D vehicle profiles, measurement, and modeling of the acoustic footprint will improve the prediction of the noise response.

Security and Privacy

Although there are many benefits of UAV services, there are also potential vulnerabilities. For example, UAVs flying illegally may pose threats and danger to human lives and infrastructure. Detecting such threats requires surveillance radars with the capability to detect and track as well as measures to safely disengage such “rogue” UAVs. There is also a need for encrypting and authenticating the information being shared by UAVs for mission-critical applications. Finally, link robustness to interference (unintentional) or jamming (intentional) must be investigated for each link type (CNS).

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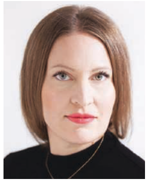

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