



IEEE Trial-Use Standard for Aerial Network Communication

IEEE Communications Society

IEEE Vehicular Technology Society

Developed by the
Mobile Communication Networks Standards Committee
and the
Intelligent Transportation Systems Committee

IEEE Std 1920.1™-2022

STANDARDS

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Developed by the

Mobile Communication Networks Standards Committee
of the
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Intelligent Transportation Systems Committee
of the
IEEE Vehicular Technology Society

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IEEE SA Standards Board

Abstract: IEEE Std 1920.1 defines air-to-air communications for self-organized ad hoc aerial networks. It outlines the network service architecture, security framework, and data model. IEEE Std 1920.1 is agnostic to the type of network (Wireless or Cellular or other) and it is applicable to manned and unmanned, small and large, and civil and commercial aircraft systems. IEEE Std 1920.1 is the first in the series of IEEE P1920.X standards. It is anticipated that IEEE Std 1920.1 will be used as a foundation to define more specific standards in this series.

Keywords: aerial networks, ad hoc network, beyond radio line-of-sight communications (BRLOS), IEEE 1920.1™, self-organized aerial networks (SOANs), unmanned aircraft (UA), unmanned aircraft systems (UAS)

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Introduction

This introduction is not part of IEEE Std 1920.1-2022, IEEE Trial-Use Standard for Aerial Network Communication.

The journey toward developing standards for aerial networks began in September 2016. The need for possible solutions to prevent accidents in the air such as the loss of Malaysian Airlines 370 or, at least, solutions to know what happened to aircraft before the accident, was a motivation for creating the IEEE Std 1920.1 Working Group. One solution that the research and professional community agreed on is “global surveillance of aircraft,” which allows the whereabouts of an aircraft to be known at all times. Though it may be challenging to share the location of aircraft at all times, the benefits make it worth addressing the challenge. This challenge sets the basis for the IEEE Std 1920.1 for aerial ad hoc networks.

IEEE Std 1920.1 is intended for small Unmanned Aircraft Systems (sUAS), although it may also be applicable to other aircraft systems.

The development of IEEE P1920.2: Vehicle-to-Vehicle Communications is currently taking place.

This document contains seven clauses. The first three clauses provide an introduction and important information about IEEE Std 1920.1. The fourth clause presents an overview of aerial ad hoc networks. The fifth clause addresses network architecture, and the sixth clause addresses security architecture. The seventh clause outlines the data model with a set typical use cases.

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IEEE Trial-Use Standard for Aerial Network Communication

1. Overview

1.1 Introduction

The integration of unmanned aircraft systems (UASs) into national airspaces around the world is expected to increase global air traffic significantly, requiring the development and implementation of new technologies to maintain safety through enhanced situational awareness and air traffic management. Direct communication between aircraft systems within the radio line of sight (RLOS) and beyond radio line of sight (BRLOS) are technologies that can make significant contributions to situational awareness and traffic management.

Even though satellite and cellular based UAS traffic management (UTM) methods are being pursued in both these strategies, the latency of round-trip communication is high in comparison to direct communication between the UASs. Further, aerial communications can supplement the other two modes of communications, especially during critical times when cellular or satellite methods may become dysfunctional or be denied.

IEEE Std 1920.1™ can be implemented with radio communications systems intended to provide interoperable services to UAS, which are comprised of one or more unmanned aircraft (UA) and a controlling function. These services include communications between UAs and services on the ground, and UAs and other UAs. IEEE 1920.1 networking services provide management services and data delivery services between IEEE 1920.1 compliant devices.

IEEE Std 1920.1 is the first in the series of standards being developed to address communications in aerial networks. Other standards in the IEEE P1920.X series will address related areas, such as vehicle-to-vehicle (V2V) communications (IEEE P1920.2), networking, and security. This series is expected to evolve naturally based on the needs of the UAS research and development community.

1.2 Structure of this document

Clause 4 provides an introduction and conceptual overview of aerial ad hoc networks. Clause 5 describes the reference architecture for aerial networks and their functions and protocols. The description is general and at higher level. This standard is expected to evolve consistent with the needs of the UAS research and development community. Clause 6 describes the security architecture for aerial networks, and outlines the threat model, security sensitivities to information transfer, and security requirements. Clause 7 describes the data model and presents several use case scenarios. The data model is defined modularly starting from a basic level and is extended to include specific information needed for a given application.

1.3 Scope

IEEE Std 1920.1 defines air-to-air communications over self-organized aerial ad hoc networks and describes the reference architecture for aerial networks, where aircraft can form a network to share information with one another with or without any supporting infrastructure, such as satellite or cellular communications. This standard is intended for RLOS and BRLOS small UASs used for civil and commercial applications. The architecture can also be extended to include additional platforms, making it a useful guide for other aircraft systems. The communications and networking standards are independent of the type of network (wireless, cellular, or other).

The main objective of the IEEE Std 1920.1 data model is to define and format data consistently in a common, secure data structure that can be leveraged across the industry. This can help improve the integrity, safety, and security of the data regardless of the types of use cases, communication technologies, or diversity of the vehicles utilized. IEEE Std 1920.1 does not specify procedures or protocols that define the means to access radio-frequency spectrum and manage its use (i.e., an “air interface”).

IEEE Std 1920.1 does not specify the size, maximum take-off weight (MTOW), modes of propulsion, and other characteristics of the UAS. It is expected that most UASs with less than 250 kg MTOW can use the protocols defined in IEEE Std 1920.1. An MTOW above 250 kg would put the UAS in the scope of certification requirements that impose requirements beyond those applicable to aircraft operating communications services within the scope of IEEE Std 1920.1.

1.4 Purpose

IEEE Std 1920.1 can contribute to aviation safety by providing for enhancing situational awareness of manned and unmanned aircraft in the shared airspace through air-to-air communications facilitated by an aerial ad hoc network. As UASs become increasingly integrated into the National Airspace (NAS), there is a corresponding need for technology systems to provide enhanced situational awareness of all aircraft operating in the shared airspace. IEEE Std 1920.1 also provides a means of compliance for the network remote identification of unmanned aircraft systems, to provide information to distinguish compliant UAS users from those potentially posing aviation security risk.

The need for self-organized aerial networks in increasing the situational awareness of aircraft systems was highlighted in a working paper titled “Use of Self-organizing Airborne Networks to Monitor Commercial Aircraft Globally” presented in a May 2014 meeting of the International Civil Aviation Organization (ICAO) (see ADS-B in Europe [B1]).⁶

1.5 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

⁶The numbers in brackets correspond to those of the bibliography in Annex B.

⁷The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

1.6 Specifications

The following specifications are applicable to IEEE Std 1920.1:

- This standard supports two modes of networks: a) ad hoc mode and b) infrastructure-supported mode. In the ad hoc mode the UASs communicate directly without satellite or terrestrial communication support. The ad hoc networks may be formed when any other means of communication is not available or fail. In that case, if one or more UASs have either a cellular or satellite communication link, the UASs form a network with partial support from existing infrastructure.
- This standard is agnostic to radio communications and spectrum use. The underlying communication mechanism may be cellular or wireless or by any other means. This standard assumes that appropriate interfaces will be developed in future between IEEE Std 1920.1 and the physical communication means used by the IEEE Std 1920.1-compliant UASs.

1.7 Applicability

The aerial ad hoc networking services specified in [Clause 5](#) of this document apply to networked IP communications between a UAS and other UASs, and between a UAS and other systems on the ground. They do not apply to UAS that operate within RLOS with no networked communications apart from a private local area network and/or proprietary means of managing the flight of the UA.

UAS operations include, but are not limited to the following:

- Surveys, filming, and other UAS operations that have no fixed route structure and operate below 150 m (500 ft) in visual line of sight (VLOS) and beyond visual line of sight (BVLOS) free-flight mode. Some operations by government authorities (police, ambulance, other disaster recovery) could also fall into this class.
- Transport of goods. The UAS can operate as free flight or within a route structure yet to be defined below 150 m (500 ft), and only in BVLOS. UAS operating in this manner would come within the scope of applicable UTM standards, practices, and regulations.

UAS operations may require authorization by the regulatory authorities (i.e., Civil Aviation Authorities, for example, the Federal Aviation Administration (FAA) in the United States). The request for the authorization should be supported by a safety case with a Specific Operations Risk Assessment (SORA) developed according to the requirements of the authority charged with such authorizations.

1.8 Conformance

Under regulations at the time of publishing, implementers of this document are required to consult with and obtain approval of National Aviation Administrations (e.g., the FAA in the United States) in advance of any proposed operation of a UAS claiming conformance with IEEE Std 1920.1. Conformance with the provisions of this standard does not imply conformance with any applicable laws or regulations, and users of this standard are responsible for observing all such legal and regulatory requirements.

The ITU-R Radio Regulations (RR), as modified by World Radio Conferences (WRCs), defines the constraints on the use of spectrum in terms of radio system performance, including coexistence with other services. Regional specializations within the general constraints of the RR further limit spectrum access and use for

short range devices (SRDs) as defined, for example, by the Federal Communications Commission (FCC) in the United States, or the European Conference on Postal and Telecommunications (CEPT) in Europe.

Any UAS operator claiming conformance with IEEE Std 1920.1 shall comply with ITU-R RR, footnotes, and regional regulations that apply to the radio system interfaces that the UAS uses. In addition, any UAS operator claiming conformance with IEEE Std 1920.1 should verify that the UAS does not cause noise or interference with other UASs using the same radio system interfaces that it uses. Use of spectrum accessed by those interfaces should be coordinated.

The UAS shall comply with protocols that use the networking services defined in [Clause 5](#) of this document. These include those protocols defined by the Internet Engineering Task Force (IETF) in its Standards and Requests for Comments (RFC), and listed in the Function Profiles in the Annexes, and any additional protocols required by those IETF Standards and RFCs. The UAS shall also comply with protocols, where such are standardized, and regulations that define procedures for accessing communications media and managing spectrum according to local regulations.

Evidence of claimed conformance shall be supported by documentation of the design, production, and operational processes applicable to the UAS taking account of applicable international and regional standards and regulations. The assurance level of the design and production processes shall meet the integrity requirements appropriate to the UAS and its proposed operation as determined by application of a risk-assessment process, e.g., the SORA. Any UAS operations shall be conducted safely with serviceable aircraft. Therefore, the following applies:

- a) The components of the UAS shall be designed and manufactured according to applicable international and national standards. The UAS may require an airworthiness certification and a Certificate of Authorization (COA) obtained from a regulatory authority.
- b) The implementation of the Command and Control (C2) Link service including communications services provided by a third-party network operator (the Communications Service Provider) shall be deployed to provide coverage throughout the UAS mission:
 - 1) The service shall achieve required levels of availability and communications integrity.
 - 2) The C2 Link using the C2 Link service shall comply with transaction expiration time and continuity requirements.
 - 3) Security measures shall provide required levels of communications security.

The communication capability may be provided by satellite and terrestrial services. The networking services shall support ad hoc connectivity by means appropriate to the deployed system Concept of Operations (CONOPS), assisted by cooperative interaction between mobile devices and between mobile devices and infrastructure.

1.9 Stakeholders

The primary stakeholders for this standard include the following:

- The Radio Technical Commission for Aeronautics (RTCA)
- The European Organization for Civil Aviation Equipment (EUROCAE)⁹
- The International Civil Aviation Organization (ICAO)
- National civil aviation authorities (such as the Federal Aviation Administration of USA)
- Airlines Electronic Engineering Committee (AEEC)

⁹Information on references can be found in [Clause 2](#).

- National communications commissions (such as the Federal Communications Commission of USA)
- Aircraft manufacturing companies
- Commercial airlines
- The global air traffic control (ATC) community

1.10 Related standards development

1.10.1 3GPP

The 3rd Generation Partnership Project (3GPP) study on enhanced LTE support for connected UAVs in Release 15 addresses cellular connectivity to low altitude unmanned aerial vehicles UAVs (Pierson, Wang, and Schwager [B24]).

1.10.2 ANSI UASSC

The American National Standards Institute (ANSI) UAS Standardization Collaborative (UASSC) developed the Standardization Roadmap for Unmanned Aircraft Systems to document the current standards landscape, articulate standardization needs, drive coordinated standards activity, reduce duplication of effort, and inform resource allocation for standards participation. Version 2.0 of the roadmap was published in June 2020 [B2].

1.10.3 ASTM Committee F38 on UAS

In February 2020, ASTM International published Active Standard ASTM F3411, Standard Specification for Remote ID and Tracking [B3] after the Federal Aviation Administration (FAA) issued the Notice of Proposed Rulemaking (NPRM) “Remote Identification of Unmanned Aircraft Systems,” on December 31, 2019.

1.10.4 EUROCAE WG-105

EUROCAE WG-105 is tasked with developing European standards and guidance documents that will allow the safe operation of UASs in all types of airspace, at all times, and for all types of operations. The current focus areas are: UAS Traffic Management; command, control, and communication; detect and avoid; design and airworthiness; specific operations risk assessment; and enhanced RPAS automation (Lawrence, Steward Cobb, Gutt, et. al [B20]).

1.10.5 GUTMA

The Global UTM Association (GUTMA) is a non-profit consortium of worldwide UTM stakeholders. Its purpose is to foster the safe, secure, and efficient integration of drones in NASs. Its mission is to support and accelerate the transparent implementation of globally interoperable UTM systems (Falkov [B7]).

1.10.6 IEEE 1609

The IEEE 1609 family of standards for Wireless Access in Vehicular Environments (WAVE) were developed by the IEEE Vehicular Technology Society (VTS) for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2X) communications (Ordoukhanian and Madni [B4]). The IEEE 1609 framework is closely related to IEEE Std 1920.1 and served as the basis for defining the network architecture as well as security architecture for IEEE Std 1920.1.

1.10.7 NASA UTM project

Building on its legacy of work in air traffic management for manned aircraft, the United States National Aeronautics and Space Administration (NASA) is researching prototype technologies for UTM that could develop airspace integration requirements for enabling safe, efficient civilian low-altitude airspace and UAS operations (EUROCAE [B5]).

1.10.8 RTCA SC-228

RTCA Special Committee (SC) 228, Minimum Performance Standards for Unmanned Aircraft Systems, is working to develop the Minimum Operational Performance Standards (MOPS) for detect and avoid (DAA) equipment and a Command and Control (C2) Data Link MOPS establishing L-Band and C-Band solutions. The initial phase of standards development focused on civil UAS equipped to operate into Class A airspace under IFR flight rules. The operational environment for the MOPS is the transitioning of a UAS to and from Class A or special use airspace, traversing Class D and E, and Class G airspace. The committee published RTCA DO-362, Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial) (Dill, Hayhurst, Young, et.al [B6]), and RTCA DO-377, Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Unmanned Aircraft Systems in US Airspace (GUTMA [B10]).

1.10.9 SAE International AS-4 UCS, WG-AIR6388

Following its participation on the Federal Aviation Administration (FAA) 2017 UAS Identification and Tracking (UAS ID) Aviation Rulemaking Committee (ARC), SAE International initiated the creation of an Aerospace Information Report, AIR6388—Remote Identification and Interrogation of Unmanned Aircraft Systems. This document, to be developed by the AS-4UCS Unmanned Systems Control Segment Architecture Committee, was to provide information about current remote identification methods and practical considerations for remotely identifying UAS (Federal Aviation Administration [B9]). It was intended that AIR6388 would address multiple UAS identification methods and cover all phases of unmanned systems operations (both vehicle in-flight and vehicle powered-off on the ground), and capture various definitions, assumptions, limitations, and technologies proposed around the globe.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

EUROCAE ED-262/RTCA DO-379: Technical Standard of Aviation Profiles for ATN/IPS.

IEEE Std 802.11™, IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks.^{10,11}

IETF RFC 768, User Datagram Protocol.

IETF RFC 793, Transmission Control Protocol

IETF RFC 2460, Internet Protocol, Version 6 (IPv6) Specification.

IETF RFC 3513, Internet Protocol Version 6 (IPv6) Addressing Architecture.

IETF RFC 4861, Neighbor Discovery for IP Version 6 (IPv6).

¹⁰The IEEE standards or products referred to in [Clause 2](#) are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

¹¹IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹²

ad hoc: Established for a specific defined purpose.

NOTE—The interpretation in the context of IEEE Std 1920.1 is provided in 4.1.¹³

anycast: An anycast destination address has semantics that allow multiple routing paths to more than one destination. Anycast addressing is fully defined for IPv6, but requires specific features for IPv4. The IPv6 specification for anycast defines the meaning of certain address value to enable the required routing.

autonomous UAS: A UAS that does not allow intervention in the management of the UA's flight. (Adaptation of the definition in ICAO Doc.10019.)

autonomous operation: An operation during which a UAS is operating without any ability to intervene to manage the flight of the UA. (Adaptation of the definition in ICAO Doc.10019.)

dynamic host configuration protocol (DHCP, DHCPv6): The Dynamic Host Configuration Protocol (DHCP) provides a framework for passing configuration information to hosts on a TCP/IP network. It adds the capability of automatic allocation of reusable network addresses and additional configuration options.

dynamic link exchange protocol (DLEP): When routing devices rely on modems to effect communications over wireless links, they need timely and accurate knowledge of the characteristics of the link (speed, state, etc.) in order to make routing decisions. In mobile or other environments where these characteristics change frequently, manual configurations or the inference of state through routing or transport protocols does not allow the router to make the best decisions. The Dynamic Link Exchange Protocol (DLEP) provides a bidirectional, event-driven communication channel between the router and the modem to facilitate communication of changing link characteristics.

NOTE—This is a summary of the Abstract of RFC 8175, an IETF Standards Track RFC [B26].

dedicated short range communications (DSRC): A wireless communication system originally designed to be used for Vehicle-To-Everything (V2X) short-range communication in the USA, based on IEEE Std 802.11 operating outside the context of a Basic Service Set (IEEE Std 802.11-OCB).

free flight: The UAS flies according to the needs of the operation.

flying ad hoc networks (FANETs): A FANET combines features Mobile Ad Hoc Networks (MANETs) and Vehicle Ad Hoc Networks (VANETs) to provide network services to aircraft including UAS.

gateway: A device in a network that is on the boundary between that network and others. It may be multihomed. Typically, it provides internet access to devices connected to a shared medium, e.g., a Wireless Access Point.

layer 2 routing: Routing performed at the Data Link layer by a device that interconnects two physical media.

layer 3 routing: Routing performed at the Network Layer that interconnects IP networks. *See:* **router, routing.**

¹²*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹³Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

layer 7 routing: Routing performed at the Application Layer.

link layer: *See: OSI model.*

link-layer routing: Routing performed at the Data Link layer by a device that interconnects two physical media.

MAC layer: *See: OSI model.*

multilink: Multilink is a term used in aviation telecommunications to describe the case where multiple network interfaces share a single network address. It has been defined by International Civil Aviation Organization (ICAO) in the ATN/OSI and ATN/IPS specifications and is implemented in the Aircraft Communication Addressing and Reporting System (ACARS).

multihomed: A multihomed device has two or more network interfaces that have different host IP addresses on one or more IP networks. A router is always multihomed. A host may be multihomed.

OSI model: A 7-layer reference model of Open Systems Interconnection (OSI). It is standardized in ISO ITU-T X.200. It comprises:

- Layer 1, Physical Layer—The means of coding, modulating by a transmitting device a collection of bits onto a physical wireless and wired medium, and the complementary processes that deliver those bits to a receiving device.
- Medium Access Control (MAC) Layer—Not part of the OSI Reference Model. The procedures that a transmitting device shall use to access the physical medium, resolving contention if necessary.
- Layer 2, Data Link Layer—The procedures that enable devices capable of accessing a physical media according to the MAC protocols to exchange information according to a Data Link Control protocol.
- Layer 3, Network Layer—The procedures that enable a forwarding or routing function to select Layer 2 interfaces most suitable for forwarding to a next hop destination. This forwarding function shall be supported by a routing protocol that allows routing decisions to be implemented on such devices.
- Layer 4, Transport Layer—The procedures that enable end-to-end communication between hosts.
- Layer 5, Session Layer—The procedures and protocols that define an interaction between two identified end-points of a transport layer association. They may include encryption, such as TLS within an IPSec framework, and call upon Application Layer functions [e.g., lightweight directory access protocol (LDAP)].
- Layer 6, Presentation Layer—The syntax by which information presented to the Session Layer is encoded and decoded.
- Layer 7, Application Layer—The means that applications access underlying communications services.

The Internet architecture is an example of an adaption of the OSI Reference Model in which Application, Presentation, and Session Layers are not explicitly distinguished.

Medium Access Control (MAC) functions enable the Data Link Layer to use the services of the Physical Layer to receive and schedule the transmission of packets (frames, messages) at the Physical Layer. It is sometimes referred to as the MAC Layer, but the OSI Reference Model does not identify it explicitly.

prefix: The pattern of bits applied to an IP address to select the part of that address that identifies its network component.

relay: A device, such as a router, that transmits messages (packets, frames) received on one interface to one or more output interfaces. Routers and bridges are relays.

remote bridge: A bridge between two or more link layers where the input interface(s) to the bridge are located at one site and the output interface(s) a located at a different site.

router: A multihomed device that performs routing.

routing: Routing is the function that relays IP packets received on one interface to one (unicast) or more (multicast, anycast) interfaces toward other networks, selected according to a routing protocol and locally applied routing policies.

routing algorithm: A routing algorithm determination of a suitable path for a network packet from a source to its destination in an IP network. It uses statically configured rules and policies together with status information advertised by devices and routers in the IP internetwork to select the interface that connects to the next router one hop closer to the desired final destination.

slice, slicing: A means of segregating groups of users of network services. It may be achieved by an administrative assignment of names and addresses of hosts and routers (gateways) to form a closed user group. Resources in the network service may be reserved for the groups, e.g., to support an assurance of the quality of service provided to the group. Specific routing policies may be applied to traffic generated in the groups. Specific security measures may be applied to the group members and the traffic that they generate.

satellite service: A communications service provided by transceivers located at satellites in orbit around the Earth capable of communicating with transceivers located on UAS interconnected with terrestrial services by fixed gateway stations.

stateless address assignment, stateless auto configuration: Devices obtain an address independently, possibly using DHCP to obtain other administrative information such as a domain name. Stateless address assignment requires the default gateway implement RFC 4862.

structured route: The UAS flies according to a predetermined route.

terrestrial service: A communications service provided by transceivers located at fixed sites on the ground capable of communicating with transceivers located on UAS, interconnected with each other by fixed communications media, e.g., MCN providing 5G, LTE, HSPA, IEEE Std 802.16, IEEE Std 1609.0, IEEE Std 802.11, Wireless Direct.

unmanned aircraft system: An unmanned aircraft system (UAS) comprises a control function, termed remote pilot station (RPS) [or Ground Control Station (GCS)] if the UAS is remotely piloted, a communications link, termed the C2 Link according to ICAO terminology, and the UAS, the aircraft itself. It is considered to be a single product (e.g., RPS + C2 Link + UAS for a remotely piloted system) from a regulatory point of view.

unidirectional links: There are different forward and return links connecting a device to the Internet. The interfaces supporting each link will have different IP addresses unless the links are combined using a DLEP or multilink approach.

NOTE—This is a specialized configuration that is out of scope of this version of IEEE Std 1920.1.

WAVE: A communication stack design originally designed to be used for Vehicle-To-Everything (V2X) short-range communication in the USA, with higher layers specified in IEEE Std 1609.3 [B15] and IEEE Std 1609.4 [B16], security services specified in IEEE Std 1609.2 [B14], and lower layers based on IEEE Std 802.11 [B11] operating outside the context of a Basic Service Set (802.11-OCB). Alternative approaches to the lower layer are given by Cellular Vehicle to Everything (C-V2X) and IEEE Std 802.11bd [B12].

3.2 Acronyms and abbreviations

ACI	access category index
ACM	admission control mandatory
AIFSN	arbitration interframe space number
ATM	air traffic management
ATS	air traffic service
ASCII	American standard code for information interchange
ASN	abstract syntax notation
BRLOS	beyond radio line of sight
BVLOS	beyond visual line of sight
CCH	control channel
CONOPS	concept of operations
C2N	command, control, and navigation
C-V2X	cellular vehicle-to-everything
CW	contention window
DNS	domain name system
DSRC	dedicated short-range communications
D2D	device to device
EDCA	enhanced distributed channel access
IETF	internet engineering task force
IP	internet protocol
IPv6	internet protocol version 6
ITS	intelligent transportation systems
LLC	logical link control
LSAP	link service access point
MAC	medium access control
MIB	management information base
MLME	MAC sublayer management entity
NAS	national airspace
OSI	open system interconnect
PHY	physical layer
PICS	protocol implementation conformance statement
PNT	positioning, navigation, and timing
PSC	provider service context
PSID	provider service identifier
RCPI	received channel power indicator

RF	radio frequency
RFC	request for comments
RPIC	remote pilot in command
SAE	international society of automotive engineers
SAP	service access point
SCH	service channel
SNAP	subnetwork access protocol
STA	station
STL	satellite time and location
TA	timing advertisement (frame)
TCP	transmission control protocol
TXOP	transmission opportunity
UA	unmanned aircraft
UAS	unmanned aircraft system
UDP	user datagram protocol
UTM	UAS traffic management
VLOS	visual line of sight
VSA	vendor specific action (frame)
V2V	vehicle-to-vehicle
WAVE	wireless access in vehicular environments
WGS	world geodetic system
WME	WAVE management entity
WRA	WAVE routing advertisement
WSA	WAVE service advertisement
WSM	WAVE short message
WSMP	WAVE short message protocol
WSMP-I	WAVE identity supplement
WSMP-S	WSMP safety supplement

4. Aerial ad hoc networks

4.1 General

As the newest element sharing the airspace, integration of UASs into the civilian airspace is necessary before industry can fully realize the development and deployment of real-world commercial applications, such as transportation of people and package delivery using UASs. The success of these efforts, in turn, depends on the efficiency of communications and air traffic management (ATM) support for UASs. ATM facilitates the sharing of information related to navigation, command, and control between the aircraft, its ground control station (GCS) and air traffic service (ATS) providers, and encompasses all systems that assist aircraft to depart from an aerodrome, transit airspace, and land at a destination aerodrome.

Communications form the core of aircraft command, control, and navigation (C2N) services. Until recently, UAS flights have been restricted to visual line-of-sight (VLOS) applications. However, beyond visual line-of-sight (BVLOS) and BRLOS applications, such as wide area survey and search and rescue operations, require significant advances in C2N services, UTM and UAS identification and tracking capabilities, regulatory conformance, safety, and security.

4.2 Ad hoc networks

Many standards have been developed that enable networked as well as non-networked communications between vehicles (automobiles, aircraft, ships on the sea, spacecraft, among others), services on the ground, and with each other. This type of communications is fundamentally “ad hoc.” “Ad hoc” in the context of IEEE Std 1920.1 means that the connectivity is enabled by the availability of local wireless spectrum that are accessed by participating devices to communicate end-to-end with mobile and fixed devices in the same area of coverage or nearby areas of coverage, or remote fixed devices accessed via fixed communications infrastructure. The mobile devices may themselves be the providers of the wireless spectrum services and support a routing capability.

The connectivity enabled by the locally available wireless spectrum may change over time, possibly frequently, when physical movement of the devices places them sufficiently out of range of other devices with which they were previously in contact. Such movement may bring them into contact with other devices. The spectrum itself may become unavailable. The connectivity may persist over a long time if the wireless spectrum remains available.

Ad hoc communications using this varying connectivity may be managed entirely by the participating devices that use their own knowledge of the local spectrum. It may be maintained by infrastructure functions that direct the devices, or cooperate with them, to maintain connectivity. It may be assisted by knowledge of local infrastructure or by information supplied by infrastructure and/or supporting services to improve the quality of end-to-end communications.

The purpose of the ad hoc communication could range in scope from local to global and from private to public. Whenever the purpose lies in this range, the solutions and practices should be able to tolerate frequent changes, planned and unplanned, in connectivity and the technology providing that connectivity. Seamless, uninterrupted, end-to-end connectivity may not be guaranteed in some cases. In others, the mission criticality of the application may require significant additional constraints on the solutions and procedures so that there is continuous connectivity.

The existing practice of ad hoc communications provides valuable lessons for a standard for communications applicable to UAS. Some of the standards used in aviation systems, manned and unmanned, are adaptations to commercial off-the-shelf (COTS) systems, using them without technical changes but possibly in specialized ways. Some are customizations of COTS systems requiring technical changes or applying certain constraints that support a specific concept of operations (CONOPS). Some are designed specifically for certain types of UA and their typical CONOPS.

4.3 Enabling technology solutions for UAS communications

There are many technology solutions that enable UAS communications, defined by the following four broad categories:

- a) Wireless radio-frequency (RF) communications systems using terrestrial and satellite media that are standardized at various levels—basic access to and use of spectrum (compliant with the ITU-R Radio Regulations), protocols that enable multiple access sharing of spectrum (e.g., IEEE 802.11 and its variants), and services that are accessed via a service provider and shield the user from access and sharing protocols (e.g., the standards developed by the 3GPP for mobile data services in public land

mobile/fixed cellular networks (MCNs). The RF communications may operate within RLOS (without infrastructure) or BRLOS (with managed infrastructure).

- b) Broadcast, point-to-point, and point-to-multipoint models for distribution of information between devices. These are sometimes embedded in the spectrum sharing/access protocols, sometimes built on top of them as a network service (e.g., WSMP as defined in IEEE 1609.0), or layer 2 virtual local area networks (VLANs).
- c) Routing protocols that enable devices in the air and on the ground to communicate with each other via mobile/fixed cellular networks (MCN) implemented by terrestrial and/or SATCOM services. Examples include conventional IP unicast and multicast routing, mobile ad hoc networks (MANET) routing, or virtual private networks (VPNs) at layer 3 or as an application).
- d) Security protocols and procedures that admit eligible devices and deny access to ineligible ones to participate in medium access, device-to-device relationships, and end-to-end relationships. Every admitted device shall conform to criteria for acceptable use during its association with any service.

The protocols and procedures for admission and use shall be resilient to internal and external attacks at a level of maturity corresponding to the hazards that would be created by a successful attack.

All these technology solutions and associated processes and standards from the International Standards Organization (ISO), ICAO, the IETF, the ITU-T, the ITU-R, CEPT, FCC, ASTM, SAE, EUROCAE, RTCA, CEN/CENELEC, ANSI, and ASD-STAN provide lessons that IEEE Std 1920.1 has taken into account.

This motivates an approach to embracing a solution that is coherent in terms of future evolutions of networked communications for UAS operating in the aviation system. It is based on defining mandatory, conditional, and optional functional profiles that allow a variety of technical communications solutions to be used, together with exceptions where necessary, so that those solutions are used consistently.

4.4 UTM development

UASs are primarily regulated by federal entities such as the FAA in the United States, which has developed a roadmap for UAS integration into the NAS [B9]. The FAA has recognized that integration of a plethora of small UASs in uncontrolled airspace cannot be managed under the existing manned ATC system. For small UASs at low altitudes, a novel paradigm is emerging through research lead by NASA's UTM project, together with industry, academia, and the several FAA Designated UAS Test Sites. Over the past several years, NASA has developed its UTM concept and tested an evolving research platform with partners [B23].

The FAA is currently evaluating the NASA UTM concept through a formal Research Transition Team (RTT) partnership. Satellite communications, cellular networks, and aerial networks-based navigation and control are significant in the UTM context because they could facilitate maximal use of limited low-altitude airspace.

4.5 Communication support for ATC and UTM

4.5.1 General

In a presentation made to ICAO in May 2014, the authors pointed out that “the accident with MH370 flight shows the need for continuous global tracking of all airline flights” [B25].

Traditionally, communication support to ATM comes from satellites operating in geostationary orbit (collectively called SATCOM). Automatic Dependent Surveillance Broadcast (ADS-B) transponders have also been recommended by NextGen and the Single European Sky Air Traffic Management Research (SESAR) program as mandatory for the backbone of future air navigation systems [B8]. An aircraft equipped with a non-switchable ADS-B transponder can send out the information of the aircraft automatically as well as respond to incoming messages from an ATC ADS-B ground station. Similarly, an aircraft can respond to an ATC facility through a non-switchable secondary surveillance radar (SSR) transponder within its RLOS.

However, because BRLOS communication is not possible within the SSR and ADS-B framework (i.e., their communication is only within RLOS), ADS-B and SSR are not technically capable of global monitoring of aircraft. Additionally, ADS-B transponders can be switched off and hence their operation is not fool-proof against attacks (e.g., by hijacker, pilot, crew).

In addition to SATCOM, two alternative paradigms are currently being investigated for UTM: 4G/5G cellular communications operating on the ground, and aerial network communications operating in the mid-airspace. These three paradigms of communication support are independent, complementary, and can, by design, serve as backup to one another. They are applicable to manned and unmanned aircraft, and to small-scale and large-scale aircraft. The three levels of communication paradigms are described in 4.5.2 through 4.5.4.

They differ in terms of performance factors such as latency and data rates that they can support.

4.5.2 SATCOM

SATCOM is the most widely used technology for commercial aircraft navigation. For ocean-crossing flightpaths, such as that of flight MH370, and those remote from ATC surveillance facilities, SATCOM is the only solution for an aircraft to communicate with the ATC when it is BRLOS from ATC facilities. The geostationary orbit has the advantage that the satellite remains in the same position throughout the day, so antennas can be directed toward the satellite and maintain track. Latency in SATCOM (the time it takes for a signal to make a round trip from the aircraft to the satellite and back) is about 638 ms, as the geostationary orbit is about 22 300 mi (35 800 km) above the Earth's surface. Position, navigation, and timing (PNT) services from low Earth orbit (LEO) satellites are being used today. STL service LEO satellites provide much stronger signals than global navigation satellite systems (GNSS) such as the Global Positioning System (GPS), which is provided by medium Earth orbit (MEO) satellites. Iridium signals are 300 to 2400 times stronger than GNSS signals on the ground, making them attractive for PNT applications where GNSS signals are obstructed [B20]. However, SATCOM has several disadvantages.

First, it is a centralized solution that requires all aircraft to be equipped with SATCOM equipment, which is expensive. Additionally, it requires all aircraft to communicate to the ATC and does not facilitate direct communication between aircraft, which may be more advantageous in many situations, such as in close-proximity operations.

4.5.3 Cellular networking

Cellular networking is an alternative to SATCOM for UAS C2N services. In this strategy a UAS is like a mobile device, and the cellular network provides information management services for a UAS in much the same way as it does for a mobile device, such as mobile phone. Due to the ITU spectrum licensing constraints, cellular network signals are often limited to low elevation angle transmission at their base stations. While this limitation would limit their use for aircrafts flying at high altitudes, cellular networks are well within the reach of the low flying UASs.

4.5.4 Aerial networks

In the commercial aviation domain, aircraft-to-aircraft (or V2V) communication could facilitate global tracking of aircraft while in the air, thus avoiding incidents in which the location of an aircraft is not able to be determined. In the UAS domain, V2V communication could play an even greater role by facilitating aerial networking essential for the successful integration of UAS into the NAS. Aerial networks would enable real-time information sharing among UASs, thus enhancing their situational awareness significantly compared to current systems. In the near term, V2V communications present a solution for detect and avoid systems that could enable routine BVLOS flights by UASs as well as Airborne Collision Avoidance System (ACAS) XR for small, unmanned rotorcraft and allow for avoidance of small, unmanned rotorcraft, cooperative and non-cooperative intruders. In the future, V2V communications support autonomous system architectures for swarms of small UASs. At the same time, V2V communications has the potential to impact cyber-physical security concerns for the UTM concept.

Industry leaders involved in developing capabilities of commercial package delivery services using UAS are suggesting segregation of airspace in which UASs would follow set rules for flying below 150 m (500 ft). In this space, UASs are expected to be connected to online networks and would directly communicate with each other, allowing for the automated control of flights in real time. To realize applications such as package delivery, communication standards, and protocols need to be in place.

Innovations in geo-fencing (Johnson [B19]; Stevens and Atkins [B22]; NASA UTM [B23]; RTCA DO-377 [B27]), conflict mitigation (RTCA SC-228 [B28] and Wallace et al. [B29]), sense-and-avoid (SAE International [B30] and Muruganathan et al. [B31]), and protection of the airspace against rogue UASs (Fang, Young, and Rolland [B8] and Prevot et al. [B25]), can be designed much more efficiently with aerial networking than by other means.

5. Aerial network architecture

5.1 System overview

UAS that implement IEEE Std 1920.1 can be integrated into systems implementing a wide range of technologies and operational concepts. The systems are characterized in different manners: by network structure, routing, physical distribution of the UASs, and the effects of their mobility inside a network and between networks.

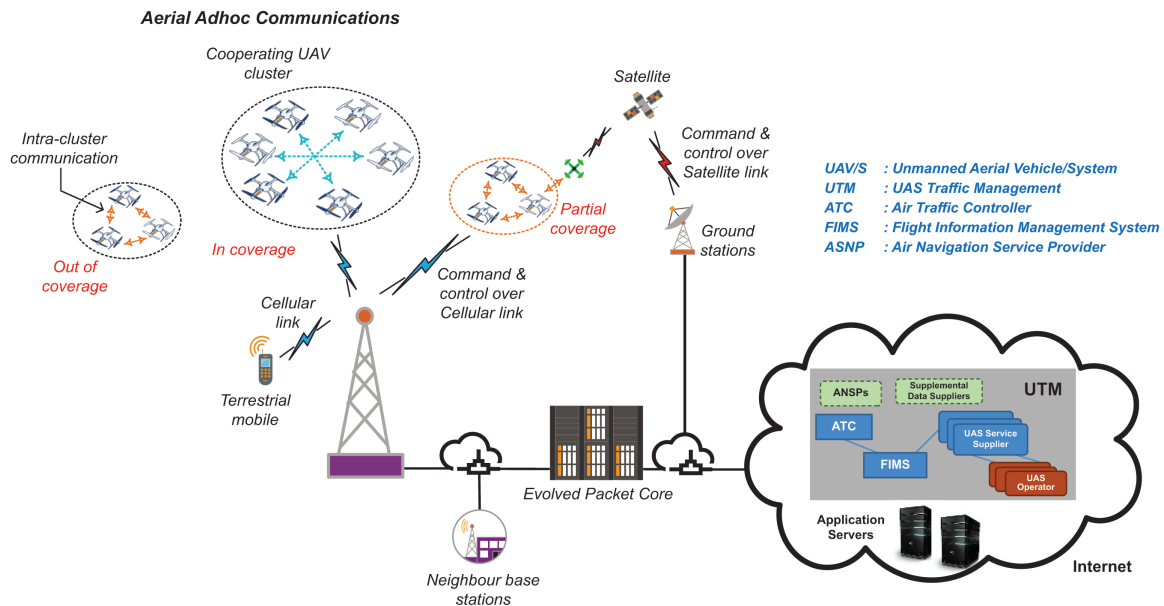
5.1.1 Network structure

Scenarios of the network structure can be placed informally into two categories and several sub-categories as follows:

- a) With infrastructure: Systems built on top of existing cellular, satellite, and short-range communications (e.g., IEEE 802.11) services including, but not limited to:
 - 1) In coverage:
 - i) Managed infrastructure connectivity only: All UASs implementing IEEE Std 1920.1 are in coverage of terrestrial or satellite services. For example, UASs communicate with each other via cellular, WAVE, or IEEE 802.11 in managed infrastructure mode provided by fixed Wireless Access Points.
 - ii) Combined managed infrastructure and local short-range connectivity for all UAS: All UASs implementing IEEE Std 1920.1 are in coverage of terrestrial or satellite services, with some or all UASs communicating with each other directly, i.e., device to device (D2D). Examples of terrestrial D2D technologies include WAVE with IEEE 802.11-OCB lower layers, WAVE with Cellular Vehicle-to-Everything (C-V2X) lower layers, IEEE 802.15, and Wireless direct.
 - iii) Combined infrastructure connectivity and local short range connectivity for some UAS: One or more of the UASs implementing IEEE Std 1920.1 are in coverage of terrestrial or satellite services, with one or more UAS communicating with each other via terrestrial or satellite infrastructure or D2D. Clusters of UASs may be able to form networks, using D2D communications (e.g., DSRC, C-V2X, IEEE 802.11) or infrastructure, and they may be able to merge from time to time, using D2D communications or infrastructure, with possible re-fragmentation, or remain fragmented.
 - 2) Out-of-coverage:
 - i) Ad hoc communications between all UASs implementing IEEE Std 1920.1 are out-of-coverage of terrestrial or satellite networks, with all UASs able to communicate using D2D communications. Clusters of UASs may be able to form networks using D2D communications (e.g., DSRC, C-V2X, IEEE 802.11) and they may be able to merge from time to time with possible re-fragmentation or remain fragmented.

- ii) UAS implementing IEEE Std 1920.1 are out-of-coverage of terrestrial or satellite networks, with some UASs unable to communicate using D2D communications. Those UASs that are unable to communicate are operating autonomously or shall implement an alternative means to communicate with a controlling entity. They are out of the scope of IEEE Std 1920.1.
- b) Without infrastructure: UAS ad hoc networks communicating direct via over-the-air interfaces such as C-V2X, DSRC supporting IEEE 802.11, or future evolutions, Wireless direct, IEEE 802.15, etc.
 - 1) In coverage: Ad hoc communications between all UASs implementing IEEE Std 1920.1 are able to communicate using D2D communications. Clusters of UASs may be able to form networks using D2D communications (e.g., DSRC, C-V2X, IEEE 802.11) and they may be able to merge from time to time with possible re-fragmentation, or remain fragmented.
 - 2) Out of coverage: Some UASs implementing IEEE Std 1920.1 are unable to communicate using D2D communications. Those UASs that are unable to communicate are operating autonomously or shall implement an alternative means to communicate with a controlling entity; they are out of the scope of IEEE Std 1920.1.

Typical configurations, with infrastructure and without, are shown in Figure 1.



^a “Terrestrial” is used in preference to “cellular.”

^b The terrestrial service or satellite service may be accessible by users who do not participate in the UAS network, e.g., a consumer mobile cellular communications network operated by a mobile network operator (MNO).

^c The terrestrial service may be accessible only to users who participate in the UAS network, i.e., the infrastructure is operated by a service provider, such as a mobile virtual network operator (MVNO) offering a private network service, emergency services provider, or law enforcement authority.

^d Satellite services. As with terrestrial services, there are several options, including the mobile satellite service (MSS), the fixed satellite service (FSS), and under certain conditions the aeronautical mobile satellite service (AMSS).

^e UAS may be multihomed with multiple network interfaces (and network addresses) and able to implement routing functions.

^f UAS may implement the multilink approach where a single network interface provides access to multiple radio access technologies using a single network address.

^g UAs may transit different categories of service during their flight moving through areas with infrastructure coverage to areas with none. The CONOPS for the mission shall identify the different configurations.

Figure 1—IEEE Std 1920.1 conformant system—Communication view