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# Airport Communications from Analog AM to AeroMACS

## 1.1 Introduction

The safety of air travel and air operations is critically linked to the availability of reliable aeronautical communications and navigation systems. Owing to the fact that flight safety is the highest priority in aviation, extreme measures must be taken to protect the aeronautical communication systems against harmful interference, malfunction, and capacity limitation.

In the early days of commercial aviation in the 1940s, analog double-sideband transmitted-carrier (DSB-TC) amplitude modulation (AM) over VHF band was adopted for aeronautical radio. This selection was made mostly for the reason that analog AM was the only fully developed and proven radio communications technology at the time. The number of VHF radio channels increased over the decades subsequent to the end of the World War II. In the 1980s, the VHF band of 118–137 MHz was allocated to aeronautical radio. With channel spacing of 25 kHz, 760 VHF AM (25-AM) radio channels became available. During the same decade, the avionics community predicted that early in the next century growth in flight operations and air traffic volume would demand communication capacity[1] that would be well beyond what was available in those days.

The air-to-ground (A/G) and ground-to-air (G/A) VHF communications system for civil air traffic control consisted of AM voice networks, where each flight domain had its own dedicated network. These networks were not interconnected and actually operated independently; however, their architecture was roughly the same. The pilot-to-control tower

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[1] Communications capacity may be defined in several different ways. Communications capacity in the context of this chapter denotes the quantity of the required aeronautical radio channels.

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(uplink; UL, also known as reverse channel or reverse link; RL) and controller-to-pilot (downlink, DL also called forward channel or forward link, FL) radio voice links were half-duplex connections and operated on a "push-to-talk" basis. Backup radio channels were provided in the event of system malfunction, power failure, or other unexpected situations. The VHF radio equipment was digitally controlled with the total of 760 channels, of which 524 channels were dedicated to A/G and G/A communications for air traffic control (ATC) purposes. The remaining channels were used by airlines for airline operational control (AOC). The AOC predominantly used and still uses a data service called the aircraft communications and address reporting system (ACARS) to manage and track the aircraft. However, the radio link can also be used for voice communications between pilots and airline agents [1]. Currently, the bulk of ground-to-ground (G/G) communications on the surface of airports is supported by wired and guided transmission systems, primarily through buried copper and fiber-optic cable loops. The G/G communications is also supported by a number of wireless systems, among them are VHF AM radio, airport WiFi system, and even some airport radar facilities.

In addition to the allocated VHF spectrum, two other spectral bands were considered to become available for aviation on a shared basis with other applications. First is an L-band spectrum of 960–1024 MHz, originally allocated for distance measuring equipment (DME). The second one is a C-band spectrum over 5000–5150 MHz, traditionally earmarked for microwave landing system (MLS). This radio spectrum was later allocated as the frequency band to carry aeronautical mobile airport communications system (AeroMACS ). AeroMACS technology is the main focus of this text and at the time of its preparation, AeroMACS was already standardized and globally harmonized as a broadband IP data communication link for safety and regularity of flight at the airport surface. Currently, AeroMACS is being tested over several major U.S. airports and, barring any unforeseen complications, it is expected to be deployed globally by the year 2020. For future airports, AeroMACS is envisioned to constitute the backbone of the communications system for the airport surface, whereas older airports can form a communications infrastructure in which AeroMACS is complimented with the airport fiber optic and cable loops that are already in place.

## 1.2 Conventional Aeronautical Communication Domains (Flight Domains)

Aeronautical signals pass through several wireless communication channels before they reach the destination. Four possible transmission links exist in aeronautical communications path: aircraft (air)-to-controller (ground), A/G; controller-to-aircraft, G/A; ground-to-ground, G/G, and aircraft-to-aircraft; A/A links. The aircraft continuously communicates with the NAS (National Airspace System), or the global airspace system, throughout the flight duration. There are several different domains (channels) through which the aircraft may be required to communicate with a ground station. Each one is a wireless channel with its own particular conditions, constraints, and characteristics. For an overall aeronautical communications system design or simulation, each of the channels listed below must be considered and characterized.

1) *Enroute Communication Channel:* This is the domain when the aircraft is airborne and A/G and G/A transmissions are required. This is essentially a high-speed mobile communication link in which the aircraft flying is at high altitude and close to its maximum speed. This link can be modeled as a simple double-ray wireless channel, or a Rayleigh fading channel. However, in the majority of cases the channel contains a line-of-sight (LOS) path and a ground reflection. When the aircraft elevation angle is high the ground reflection takes place at a point very close to the ground station, therefore, the path length between the two rays is very small and hence they cannot be resolved by the receiver [2].
2) *Flying Over a Ground Station:* This is a special case of enroute channel during which the Doppler effect changes its sign. For design and simulation of the aeronautical communications links, this mode must be considered separately from the enroute case [3].
3) *Landing and Takeoff Domain:* The aircraft is airborne at low altitudes and moving at its landing and takeoff speed, it is engaged in A/G and G/A communications and is close to the control tower. The channel is multipath with a strong LOS component.
4) *Surface (Taxiing) Channel:* In this domain the aircraft moves rather slowly toward or away from the terminal, it is therefore a low-speed low-range mobile communications affected by multipath and some Doppler effect.
5) *Parking Mode:* This mode is applicable when the aircraft is on the ground and close to a terminal and traveling at a very low speed or is parked. This requires essentially a stationary wireless transmission of low range.
6) *Air-to-Air:* This channel is used for the purpose of communications between two aircraft while they are in flight.
7) *Oceanic Domain:* This channel has its own characteristics in the sense that it is a long-range communications channel for the most parts. VHF LOS transmission is not feasible for this domain.

8) *Polar Domain:* This is also a channel in which long-range communications take place. This domain has a limited satellite access.

In some literature, communications in domain 3 is referred to as *terminal communications*. Communications over domains 3–5 together are what is referred to as *airport surface communication* in this chapter. For oceanic and remote areas, such as polar regions, since LOS transmission to ground stations is not possible, HF (high frequency) band and satellite systems are used.

## 1.3 VHF Spectrum Depletion

It was long accepted that as a rule of thumb, and baring any unexpected sudden traffic increase, the aviation traffic is anticipated to have an annual growth of at least 2%. However, the spectrum that was allocated for various functionalities of aerospace management system remained fixed, except for the abovementioned L-band and C-band that later became available on a spectrum sharing basis. The safety, security, growth, and efficient operation of national and global aviation systems are vitally dependent on reliable communications, navigation, and surveillance (CNS) services. Communications provides wireless and wireline connections for voice and data exchange between various entities involved in the aviation system, that is, aircraft, airports, terminals, runways, control towers, satellite transponders, and so on. The other essential component of aviation system is the air traffic management (ATM) system that heavily relies on communications and surveillance components of CNS [4].

In the late 1990s, the demand for aeronautical communications links surpassed what the existing VHF radio channels could supply without unacceptable level of interference. In the United States, rapid increase in air traffic due to commercial transportation and general aviation (GA) (private aircrafts) was the culprit. In Europe, owing to an almost exponential growth in commercial flights in the 1990s, the problem was more severe. Besides, many major European airports with large volume of air traffic are located at close geographical proximity of each other. In the early 2000s, the Europeans proposed a scheme in which 25 kHz spacing band is reduced to 8.33 kHz and thereby the number of available radio channels is tripled to 2280. This scheme that became known as "8.33-AM" ran into some standardization problems and was not implemented in the United States although it was accepted and deployed in Europe.

As the capacity of VHF aeronautical radio was reaching saturation in the United States and in Europe, the International Civil Aviation

Organization[2] (ICAO) at its 11th Air Navigation Conference held in September 2003 made a number of recommendations. One recommendation specifically called for exploration of new terrestrial and satellite-based technologies on the basis of their potential for standardization for aeronautical mobile communications use. A second recommendation asked for monitoring emerging communications technologies but undertaking standardization work only when the technologies can meet current and emerging ICAO ATM requirements. These requirements asked for technologies that are technically proven, meet the safety standards of aviation, are cost-effective, can be implemented without prejudice to global harmonization, and are consistent with Global Air Navigation Plan (GANP) for CNS/ATM.

The key functional objective for future aeronautical communications systems was deemed to provide relief to the congested VHF aeronautical band by either substantially increasing the number of voice channels or using the spectrum more efficiently or a combination thereof. In doing so, one could contemplate several options. A direct possibility was using the available VHF band more efficiently by introducing new communication technologies that save spectrum. The other option was utilizing the available VHF spectrum more efficiently by reducing the channel spacing and guard bands. Another approach was incorporating data communications links such that the majority of required voice messages can be transmitted more efficiently by data and text messages. Yet, another alternative was to take advantage of appropriate frequencies outside of the aeronautical VHF band that were available on a shared spectrum basis. One could also contemplate applying technologies such as GPS and other satellite-based technologies that have their own allocated spectrum and are suitable for carrying some components of aeronautical communications [4].

## 1.4 The ACAST Project

In 2003, NASA initiated an R&D project for future CNS/ATM infrastructure that was termed as "Advanced CNS Architectures and Systems Technologies"; ACAST. The main objective of the ACAST project was to define a transitional architecture to support the transformation of the present day patched-together CNS infrastructure into an integrated

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[2] "The International Civil Aviation Organization is the global forum of States for international civil aviation. ICAO develops policies, standards, undertakes compliance audits, performs studies and analyses, provides assistance, and builds aviation capacity through the cooperation of Member States and stakeholders" [5].

high-performance digital network-centric system. This was to take place, perhaps, through technologies that can be implemented in near-term and midterm to address the airspace urgent needs, while they can simultaneously be a part of the long-term solution. It was suggested that one long-term solution that is most cost-effective and can support present and potential future requirements is a network-oriented hybrid of satellite and ground-based communication systems. It was further recommended that all ATM and nonpassenger enroute communications be handled by the satellite-based technology, and all terminal and surface communications be placed on the ground-based system [6]. The ATM communications consists of several components: ATC that includes CPDLC (controller–pilot data link communications) – a method by which control tower can communicate with pilots via data and text (to be discussed in Section 1.5.4)-, automatic dependent surveillance (ADS), National Traffic Information Service (NTIS), AOC, and advisory service; such as flight information services (FIS) and weather sensor data downlink.

There were 10 partially overlapping subprojects envisioned in the ACAST project. The first three subprojects were considered foundation or "guiding frameworks" for other technology development in the ACAST project. The first was *Transitional CNS Architecture* philosophy in which the key requirements for CNS transitional architecture were increased integration of data transmission, full A/G network connectivity, high capacity, global coverage, efficient use of spectrum, and capability to evolve into a long-term CNS architecture. The second subproject was *Global A/G Network*. This formed the backbone of the CNS infrastructure. The major feature of this network was full CNS information sharing with all network users. The required protocols that were gradually emerging indicated that the Internet techniques are likely to be applied in A/G network as well. The third subproject was related to *Spectrum Research*. There was and is an ever-increasing demand for spectrum for aviation, thus efficient usage of the spectrum and development of new CNS technologies that would use the available spectrum to meet the future needs of aeronautical applications was deemed to be a key component of the ACAST project.

Another ACAST subproject was "VHF systems Optimization." This subproject investigated the methods and techniques that optimize the performance of the then VHF aeronautical band [6].

In meeting the key functional objectives of VHF aeronautical communications, one should not lose the sight of the strategic objectives of the global airspace system; that the change must be cost justified, it should be globally applicable and interoperable, and it should allow a smooth transition for service providers and users, and should avoid needless avionics [7]. In providing short-term or midterm resolution to congestion problems, it would be prudent and desirable to ensure that the technology under consideration has the potential of becoming a part of the long-term solution, and is able to furnish a smooth transition from present to near-term and to long-term aeronautical communication system.

## 1.5 Early Digital Communication Technologies for Aeronautics

For over three decades, analog VHF DSB-AM system represented the dominant radio technology for aeronautics. In the late 1970s and early 1980s, data communications techniques gradually permeated into aeronautical information exchange systems; following the general trend in the then telecommunications industry, morphing into computer communication era. In this section, pre-AeroMACS digital communications schemes applied and implemented for aeronautics, as well as technologies that were considered for this application but were never implemented, are briefly reviewed in a historical context.

### 1.5.1 ACARS

The application of digital communications in civil aviation began with the introduction of Aircraft Communications Addressing and Reporting System (ACARS) technology in 1978. ACARS is a data communications scheme designed and commercialized by Aeronautical Radio, Inc. (ARINC) for short burst message communications between the aircraft crew and control tower, national aviation authorities, and airline operation centers. In other words, ACARS transmission link carrying operational information for AOC. ACARS is a packet radio system with a data rate of 2400 bps using DBFSK (differential binary frequency shift keying) modulation, operating over VHF AM channels. Burst messages in ACARS are limited to contain no more than 220 characters and transmission often lasts less than one second. To provide data integrity over ACARS link, CRC codes and automatic repeat request (ARQ) protocol are applied to each packet. Information carried by ACARS, often automatically sent without requiring any pilot action; ranging from departure and arrival time to reports on engine parameters that alert the ground maintenance crew that a fault requires attention upon the arrival of the aircraft. Over the past two decade, ACARS has been extended to provide assistance in air traffic control by transmitting text in lieu of voice messages. This reduces the need for voice channels since spoken English is converted to written messages, a feature that is most desirable for foreign pilots. However, ACARS has many limitations that prevented its consideration as a contender for next generation of

VHF data communication link. The primary shortcoming of ACARS is that it is a message link and as such it allows the transmission of a maximum number of textual characters, thus it is constrained by presentation and the length of the message that it can transmit.

### 1.5.2 VHF Data Link (VDL) Systems

In the late 1990s, ICAO endorsed the concept of supplementing VHF voice communications with data links. It has been shown that air traffic controller workload is directly proportional to the ongoing amount of voice communications. With the introduction of data communications through ACARS, voice traffic was shown to have dropped dramatically [8], that is, data transmission offers a more efficient use of the spectrum.This lead to the development of VHF Data Link Systems.

#### 1.5.2.1 Aeronautical Telecommunications Network (ATN)

The Aeronautical Telecommunications Network (ATN), which is the international infrastructure that provides support for digital data transport, was originally envisioned to provide features such as network mobility and multiple data link availability [9]. Four A/G applications of ATN were originally standardized; Controller Pilot Data Link Communications (CPDLCs) that replaced most of the functions of the controller–pilot voice interaction with text messages, Automatic Dependent Surveillance (ADS) data was designed to provide position information to the ground station, digital flight information services (D-FIS) that allows the pilot to continuously receive information about flight conditions, and context management (CM) that enables the aircraft to contact local air traffic authorities.

More recently, ICAO has developed a new standard for ATN that is based on the Internet protocol suite, which is referred to as ATN/IPS, to replace the legacy OSI-based ATN. ICAO has also authored a technical manual for this new international ATM infrastructure. The manual contains the minimum communication standards and protocols that will enable implementation of ATN/IPS. The ATN/IPS has adopted the same four-layer model as defined in the Internet standard STD003. This model has four layers called the link layer, the Internet protocol (IP) layer, the transport layer, and the application layer. The manual adopts the Internet protocol version 6 (IPv6) for Internet layer interoperability [10].

#### 1.5.2.2 VDL Systems

To expand on ACARS capability, VHF data link (VDL) schemes were developed. VDL features a bit-oriented digital transmission technology with different modes that provide various transmission capabilities.

**Table 1.1** The key physical layer parameters of VDL, 25-AM, and 8.33-AM.

| Technology | 25-AM | 8.33-AM | VDL Mode-2 | VDL Mode-3 | VDL Mode-4 | VDL Mode-E |
|---|---|---|---|---|---|---|
| Modulation scheme | DSB-TC (AM) | DSB-TC (AM) | D-8PSK | D-8PSK | GFSK | D-8PSK |
| Pulse shaping | N/A | N/A | Raised cosine | Raised cosine | Gaussian | Raised cosine |
| Channel coding | N/A | N/A | (255, 249) RS Code | (72, 62) RS Code | None | (72, 62) RS Code |
| Data rate | N/A | N/A | 31.5 kbps | 31.5 kbps | 19.2 kbps | 31.5 kbps |
| Transmission mode | Voice | Voice | Voice | Voice and data | Data | Voice and data |
| Access method | FDMA | FDMA | CSMA | TDMA | STDMA | TDMA |
| Channel spacing | 25 kHz | 8.33 kHz | 25 kHz | 25 kHz/4 time slot | 25 kHz/4 time slot | 8.33 kHz/2 time slot |
| No. of radio channels | 760 | 2280 | 380 | 3040 | 760 | 4560 |

Table 1.1 summarizes key physical layer parameters of different modes of VDL networks. For comparison purposes, the same information is provided for analog VHF schemes of 25-AM and 8.33-AM.

*VDL Mode-2* was designed as a data-only transmission system to replace and upgrade ACARS that provides AOC, ATS (Air Traffic Services), and ATC (Air Traffic Control) communications. The VDL Mode-2 uses carrier sense multiple access (CSMA). This protocol permits statistically equal channel access to the users. Consequently, an increase in traffic translates into access delay making VDL Mode-2 unsuitable for time-critical data [11]. It should be noted that within the past three decades or so, VDL Mode-2 has emerged as the selected pre-AeroMACS digital communications standard for aeronautics.

*VDL Mode-3* was developed by the FAA (Federal Aviation Administration) and industry partners, and was considered at the time as the next-generation airborne communications system (NEXCOM) for ATS. VDL Mode-3 is a digital TDMA system providing four time-slots over the existing 25 kHz voice channel, thus it quadruples the spectral capacity of the VHF system. Other key features of VDL Mode-3 are as outlined further.

- VDL Mode-3 provides the capability of simultaneous transmission of voice and data over a single RF channel.

- Since VDL-Mode 3 is spectrally compatible with the existing 25 kHz AM system, it allows a straightforward transition from the legacy technology.
- VDL Mode-3 offers improvement on safety and security relative to existing analog AM-DSB scheme.
- VDL Mode-3 features automatic channel selection, thereby reducing the pilot's workload.

VDL Mode-3 permits a smooth transition from the analog AM system in the United States. However, with the deployment of the 8.33 kHz AM system in Europe, its international implementation faced serious frequency management challenges due to its spectral incompatibility with AM-8.33 [11].

*VDL Mode-4* is a data-only broadcast scheme that was originally developed for surveillance; however, it was adapted for communication use in the 1990s. VDL Mode-4 uses a self-organizing TDMA MAC layer where time slots are scheduled by a ground system to provide a nearly equal access to the channel. This scheme is based on cellular technology that requires low SNR that could increase the frequency reuse factor in the surface and terminal domains. Standards are being developed for VDL Mode-4 to be used for point-to-point communications with applications in A/A data transmission.

*VDL Mode-E* proposed by Rockwell Collins Inc. is a modified version of VDL Mode-3. As such it applies many protocols defined for VDL Mode-3. The most significant difference between the two technologies is that Mode-E requires a channel spacing of 8.33 kHz and each channel provides two TDMA time slots. Consequently, VDL Mode-E increases the capacity of VHF legacy system by sixfold. With six data–voice-integrated channels accommodated by a single 25-AM channel, VDL Mode-E provides the best spectral efficiency of all VDL technologies. It has been suggested that VDL Mode-E meets all of the European safety and security requirements for the next-generation integrated voice/data aeronautical communications [12]. However, spectral incompatibility of VDL Mode-E and the present 25-AM system is an issue that can create standardization problems.

*LDL* (L-band data link) technology is a hybrid derivative of VDL Mode-3 and Universal Access Transceiver (UAT) standards. LDL inherits its physical layer protocols from UAT, and its upper layer standards from VDL Mode 3.

### 1.5.3 Overlay Broadband Alternatives for Data Transmission

Following the development of VDL technologies, it was recognized that the overall capacity of VHF aeronautical communication network may be further enhanced when message and text broadcast capabilities are supported. One rather straightforward method that was considered was a transmission system that uses the entire allocated VHF spectrum while it can coexist with the legacy VHF AM network, that is, to say broadband overlay schemes. A couple of alternatives were available.

#### 1.5.3.1 Direct-Sequence Spread Spectrum Overlay

A key property of direct-sequence spread spectrum (DSSS) signaling is its capability to overlay narrowband signals without introducing excessive interference to them, provided that a proper process gain is selected for the wideband signal. On the other hand, since DSSS signals are tolerant of interference and jamming, they will be immune from the interference effects of the narrowband AM signal to a certain extent. Several studies have indicated that under certain circumstances, it is feasible to overlay CDMA (Code Division Multiple Access) signals in various VHF aeronautical bands while AM legacy signals occupying parts of the band [13]. The near–far problem is observed in the sense that the AM signal transmitted by an aircraft that is far away from the ground station is attenuated and becomes more vulnerable to DSSS signal interference at the ground station, which is broadcasting the spread spectrum signal. On the other hand, DSSS signal is attenuated greatly by the time it is received by an aircraft flying at some distance from the ground station and is likely to be jammed by the AM signal transmitted by the aircraft. Nonetheless, it has been shown that the overly of DSSS signal in the VHF band was a viable solution to the spectral congestion in VHF aeronautical communication.

#### 1.5.3.2 Broadband VHF (B-VHF)

The broadband VHF (B-VHF) is an overlay scheme based on multicarrier modulation (OFDM), which was under development as a possible future aeronautical communications technology in Europe. This was a promising technology that had the potential of fulfilling many functional and strategic objectives of the future long-term-integrated CNS network. Since there are always some unused 25-AM channels at any given time, as well as channels that are being used so far away that the received signal power is small enough to assume those channels are unused, spectral gaps so available in VHF band could have been used to launch B-VHF signals. In other words, B-VHF would not require a continuous part of the VHF spectrum but could operate in the VHF band spectral gaps, and therefore, would reject interference from the legacy VHF signals. On the other hand, the B-VHF overlay signal would produce a minimal amount of interference toward the legacy AM system [14].

The enabling technology in B-VHF is OFDM, which is also the technology employed in fourth-generation (4G), and perhaps will also be used in fifthgeneration (5G) mobile communication. For these reasons, B-VHF was a particularly attractive technology candidate for future aviation communications. Besides, OFDM had already been successfully applied in digital audio and video broadcast systems and was considered as a candidate for future commercial mobile communication systems, thus aeronautical communications would be benefiting from hardware and software development that had already been made in OFDM technology.

### 1.5.4 Controller–Pilot Data Link Communications (CPDLC)

In the early 2000s, the Federal Aviation Administration launched an ICAO-compliant enroute digital communications capability, known as controller–pilot data link communications (CPDLC), into the NAS, see Section 1.7). CPDLC is a data link application supporting a number of services such as ATC communications management (ACM), clearance request and delivery (CRD), ATC microphone check (AMC), departure clearance (DCL), data link taxi (D-TAXI), oceanic clearance delivery (OCL), 4-D trajectory data link (4DTRAD), information exchange and reporting (IER), dynamic required navigation performance (DRNP), and so on. In essence, CPDLC replaces voice commands and requests with small text messages using Abstract Syntax Notation 1 (ASN-1) format.

The main objectives of CPDLC is to improve the safety and efficiency of ATM. It is well known that approach and landing are the most critical phases of a flight taking place over TMA (terminal maneuvering area). TMA is a designated area of controlled airspace surrounding an airport and characterized by high volume of air traffic, demanding higher pilot and controller workload and performance requirements. The evident advantages of using CPDLC over VHF voice communications include higher spectral efficiency over analog voice, incorporation of error control to ensure accurate reception of the messages, text display of the messages enabling the review of the messages at later time, accent-independent communications, and so on.

The CPDLC digital signals are transmitted through VDL Mode 2 at the speed of 31.5 kbps, protected by a (255, 249) Reed–Solomon code (see Table 1.1), for controller–pilot communications. In remote flight domains, the interchange may be carried out by satellite, HF, or other available suitable data link(s). General performance requirements for CPDLC links are defined by ICAO, as listed further [15].

i) The probability of nonreceipt of a message will be equal to or less than $10^{-6}$.
ii) The probability that nonreceipt of a message will fail to be notified to the originator will be equal to or less than $10^{-9}$.
iii) The probability that a message will be misdirected will be equal to or less than $10^{-7}$.

The CPDLC messages are comprised of message elements, selected from a message set, that are used to fabricate messages that support particular operational intents. ICAO has assembled the list alongside with the definitions and functional intents of these messages in a document. The CPDLC messages are labeled with two security/priority attributes. The first is urgency attribute which defines the queuing requirements for received messages that are displayed to the end user. Urgency attributes, in the order of precedence, are classified as distress (D), urgent (U), normal (N), and low (L) types. Second is alert attribute that delineates the type of alerting required upon the receipt of the message. Alert attributes are classified, in the order of priority, as high (H), medium (M), low (L), and no alerting required (N) types. Table 1.2 provides a sample of uplink

**Table 1.2** Samples of CPDLC responses, acknowledgements to messages, and attributes.

| Message element | Direction | Message intent | Urgent | Alert |
|---|---|---|---|---|
| STANDBY | Uplink | ATC has received the message and will respond | N | L |
| REQUEST DEFERED | Uplink | ATC has received the request but deferred until later | N | L |
| REQUEST ALREADY RECEIVED | Uplink | Indicates to the pilot/crew that the request has already been received on the ground | L | N |
| ROGER 7500 | Uplink | Notification of receipt of unlawful interference message | U | H |
| EXPECT DESCENT AT (time) | Uplink | Notification that an instruction should be expected for the aircraft to commence descent at the specified time | L | L |
| DESCEND TO REACH (level) BY (position) | Uplink | Instruction that a descent is to commence at a rate such that the specified level is reached at or before the specified position | N | M |
| WILCO | Downlink | The instruction is understood and will be complied with | N | M |
| REQUEST (level) | Downlink | Request to fly at the specified level | N | L |
| REQUEST DESCENT TO (level) | Downlink | Request to descend to the specified level | N | L |
| REQUEST VMC DESCENT | Downlink | Request that a descent be approved on a see-and-avoid basis | N | L |

(pilot-to-controller) and downlink (controller-to-pilot) CPDLC messages along with their urgent and alert attributes.

The complete list of CPDLC uplink and downlink messages and responses and/or acknowledgements with their assigned urgent and alert attributes are provided in Appendix A of Ref. [16].

## 1.6 Selection of a Communications Technology for Aeronautics

In selecting a communications technology that would address the aeronautical spectral capacity problem and would simultaneously define transition architecture to support transformation to a long-term network-centric CNS system, a number of issues must be considered. The following presents a key, but partial list:

- *Capacity Enhancement:* A major reason for technology change was to increase spectral capacity of the aeronautical radio network.
- *Spectral Compatibility:* A given technology is efficiently implemented over a section of the RF spectrum. Clearly, this spectrum should overlap with that of VHF aeronautics.
- *System Compatibility:* The new configuration should be compatible with the old one, that is, the user should be able to utilize the old system with no difficulty.
- *Cost Efficiency:* This involves the cost of on-board and ground avionic systems.
- *Ease of Architectural Integration:* This is concerning whether the technology poses a significant technical challenge for getting integrated into a standard architecture of aeronautical communications.
- *Interoperability:* The new technology must have been interoperable with other standardized systems already in place globally.

A number of candidate terrestrial and satellite-based communications technologies, operable over the aeronautical VHF band, were identified and investigated for long-term resolution of the spectral depletion problem in the national and global aeronautical radio. These technologies that were already proven viable in other applications included narrowband VHF data link (VDL series), wideband VHF (B-VHF), various cellular communications formats, wireless LAN (the IEEE 802.11 standard family), wireless MAN (IEEE 802.16 standard-based system; WiMAX) satellite communications, public safety radio communication systems, and dedicated terrestrial or satellite-based technologies that might have been developed for aviation applications [4].

In 2004, the FAA, in close cooperation with EUROCONTROL, initiated a study that became known as future communications studies (FCS) [17]. This was essentially a technology assessment effort in which over 60 different commercial, public safety, and government communications services and standards were evaluated for applicability for communications over various aeronautical domains. Based on this technology assessment, it was recommended that, as the starting point for airport surface domain, the wireless mobile communications technology based on IEEE 802.16e (Mobile WiMAX) should be selected [18]. This led to the birth of aeronautical mobile airport communications system (AeroMACS).

Over the past few years AeroMACS has evolved from a technology concept to a deployed operating communications network over a number of major U.S. airports. It is expected that AeroMACS will be deployed globally by the year 2020. WiMAX Forum is in charge of composing profiles for WiMAX-driven technologies, including AeroMACS. The most recent version of AeroMACS System Profile that is based on WiMAX Forum Mobile System Profile Release 1 was published in 2013 [19].

## 1.7 The National Airspace System (NAS)

The infrastructure within which the U.S. aviation system operates is the NAS. NAS is a complex network of airports, airways, air traffic control facilities, and all the associated rules and regulation designed to supervise safety of flights for civil (commercial as well as private) and military aviation in the United States, and to manage expeditious movement of the aircraft from the point of origin to the destination in an efficient manner. As such NAS is the network (or multinetwork) of towered and non-towered airports and landing areas, communications facilities, navigation and surveillance equipment, services and applications, technical information tables and data charts, manpower, and so on, that support safety, security, and regularity of flights over the U.S. airspace. The national airspace system is supervised by the Federal Aviation Administration, and consists of three major components, area control facility (ACF) equipment, remote communications facility (RCF) equipment, and transport media. To conform to international aviation standards, the United States adopted the primary elements of the classification system developed by the ICAO.

Originally, NAS was designed for civil aviation with three hierarchical objectives in mind. First and foremost is the safety of the flight, whereas the second objective is the expeditious movement of the aircraft from the point of origin to destination. The final objective is the conduct of efficient air transportation operation. Consequently, with safety of flight being the primary concern, the use of airport facilities, the design and operation of the ATC system, the flight rules and procedures employed, and the conduct of operations are all guided by the principle that safety is the first consideration [20].

The second objective is to permit aircraft to move from origin to destination as rapidly as possible without compromising the safety of the flight. This improves the traffic-handling capacity of the system and it involves preventing conflicts between flights, avoiding delays at airports or enroute, and eliminating inefficient or roundabout flight paths. It also entails making maximum use of airport and airway capacity in order to satisfy demand, so long as safety is not compromised. If safety and capacity utilization are in conflict, the FAA operating rules require that the volume of traffic using the system be reduced to a level consistent with safety.

The third objective is about making airport and air traffic control process cost efficient, again without compromising the safety. This implies not only the optimization of monetary cost to the users, but also the minimization of penalties of delay, inconvenience, undue restriction, and this sort of items. It also entails operating the system as efficiently as possible so as to reduce transaction costs and to increase productivity, that is, to handle more aircraft or to provide better service to those aircraft with a given combination of runways, controllers, and ATC facilities.

It should be noted that although safety cannot be compromised in the interest of cost efficiency or capacity, capacity and cost efficiency may be traded off for the sake of safety. For instance, in the event of workforce reduction in the air traffic control sector, the number of aircraft allowed to use certain crowded airports and air ways at peak demand hours is lowered to a level that safety is not compromised. Clearly, this measure reduces the NAS capacity, meaning that the aggregate number of flight transactions (landing and takeoff) handled by the system's airports would be cut back.

### 1.7.1 Flight Control

Flight safety for civilian and military aviation over the NAS relies on the three components of CNS. In order to ensure proper functioning of CNS, an aircraft remains in continuous communication with the NAS (i.e., controllers) from the time it boards the crew and passengers at the airport of origin to the time it parks at a gate in a terminal of the destination airport. In what follows, the procedure through which an aircraft and the NAS stay in contact is explained.

Initially, the pilot is provided with preflight information from one of the flight service stations (FSS). There are currently six FSSs in operation in the NAS. The preflight information consists of data that is related to the aircraft rout of flight such as weather conditions briefing.

The U.S. airspace is divided into 22 three-dimensional “cells” or regional sectors, each sector is controlled by an air route traffic control center (ARTCC). Originally, the aircraft communicates with air traffic control tower (ATCT) of the airport from which the flight is originated. As the aircraft moves away from the airport of origin, it gets connected to its regional sector ARTCC. When the aircraft crosses the boundary of its original ARTCC into a new sector, the controller transfers the communications responsibility for the flight to the new sector’s ARTCC, a process that is analogous to handover procedure in cellular networks.

When the aircraft gets to the proximity of the destination airport, the ARTCC controllers hand off the communications with the aircraft to the Terminal Radar Approach Control (TRACON) controllers. The TRACON controller is responsible for assisting the aircraft for the landing process.

Once an aircraft enters an airport area, the communications is handed off to the local ATCT controllers, who are responsible for the aircraft movement control and for supervising its final approach and landing. The ground controllers, who foresee aircraft taxing to the selected gate and the gate operation, are also a part of ATCT.

Current communications technologies supporting flight control for safety and security include classical ground-based radar systems, standard VHF and UHF radio, controller–pilot data link communications (CPDLC), ACARS, GPS, and the airport wireline cable loop system. For instance, the ground-based radar signals are interpreted, converted to digital form, and sent to computer monitors at ARTCC, TRACON, or ATCT. These technologies served the NAS adequately until the late 1990s and early 2000s. However, as time rolls by, crowded airports and runways, delays, wasted fuel, and lost revenues are evidently seen to be on the rise. FAA next-generation air transportation systems (NextGen) program promises to dramatically overhaul the current NAS by finding techniques that can combat the current challenges.

### 1.7.2 United States Civilian Airports

Airports are the center piece of the national airspace system. In a broad and inclusive sense, an airport is any location that is designed and equipped, or even just commonly used, for the landing and takeoff of aircraft. This all-encompassing definition covers a wide spectrum of sites, from dirt strips that are designated as airports by the FAA to Hartsfield–Jackson Atlanta International Airport, the busiest airport in the globe in the passenger traffic sense (over 101 million passengers in the year 2015). Figure 1.1 shows an aerial view of the Atlanta Airport.

**Figure 1.1** An aerial view of Hartsfield–Jackson Atlanta International Airport.

Aerodromes that are exclusively utilized for helicopter landing and takeoff are called heliports. An airport for use by seaplanes and amphibious aircraft is called a seaplane base. Such a base typically includes a stretch of open water for takeoffs and landings and seaplane docks for tying-up. The minimum requirement for an area to be called an airport is the availability of a runway strip, on land or on water, that can be totally or partially used for arrival, departure, and surface movement of aircraft.

Airports may be classified in a variety of ways. In Chapter 3 it is pointed out that when characterizing airport surface radio channels, airports are identified as small, medium, or large; depending on their landmass sizes and configurations. In compliance with the Airport and Airway Development Act of 1970, the FAA maintains a master list of airport development needs for the next decade. This list, which is periodically reviewed and revised, is called the National Airport System Plan (NASP). NASP classifies nonmilitary airports, according to their aviation functions, into national, domestic air carrier, commuter, reliever, and general aviation (private aircraft). This does not imply that private aircraft only use general aviation airports. In fact, privately owned aircraft operate at all types of airports, however, general aviation airports exclusively serve private aircraft [20].

More recently, the FAA has categorized U.S. airports in accordance with their eligibility to receive AIP (Airport Improvement Plan or Program) funding. Publicly used airports that are listed in the National

**Table 1.3** Primary airport classification [21].

| Primary airport | Large | Medium | Small | Nonhub |
|---|---|---|---|---|
| Common name | Large hub | Medium hub | Small hub | Nonhub primary |
| Percentage of total national passenger boardings | No less than 1% | More than 0.25%, but less than 1% | At least 0.05%, but less than 0.25% | More than 10,000 boardings but less than 0.05% |

Plan of Integrated Airport Systems (NPIAS) are eligible to receive this funding. From the legal point of view "An airport is defined in the law as any area of land or water used or intended for landing or takeoff of aircraft including appurtenant area used or intended for airport buildings, facilities, as well as rights of way together with the buildings and facilities" [21]. The law categorizes airports by type of activities, including commercial service, primary, cargo service, reliever[3], and general aviation airports [21]. *Commercial service airports* (CSA) are defined as publicly owned airports with at least 2500 annual passenger boardings, including passengers who continue on an aircraft in international flight that stops at an airport in any of the 50 states for a nontraffic purpose, such as refueling or aircraft maintenance. Passenger boardings at airports that receive scheduled passenger service are referred to as *enplanements*. Commercial service airports are further classified into *primary* and *nonprimary* airports. Nonprimary airports are small airports with no more than 10,000 annual passenger boardings. Primary airports, on the other hand, are further classified in accordance with their level of air-traffic handling, that is, the percentage of the total national passenger boardings. This classification is presented in Table 1.3.

U.S. airports may also be classified as towered and nontowered airports. A large number of general aviation airports are nontowered, while all commercial airports are towered. It is estimated that there are about 12,000 nontowered airports in the United States. Currently, the FAA plans to install AeroMACS networks only on towered airports. As far as AeroMACS is concerned, the total number of towered airports and how they are distributed across the contiguous part of the United States land is an important factor for computation or estimation of the level of interference that AeroMACS imposes onto coallocated applications. In particular, AeroMACS interference to the feeder links of non-geostationary satellite

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[3] Reliever airports are special airports, designated by the FAA, to relieve congestion at CSAs and to provide improved general aviation access to the overall community [21].

systems in the mobile satellite service (MSS) is a critical AeroMACS design issue that limits the output power level, as well as the orientation, of AeroMACS antennas on the surface of airports. The Globalstar Satellite Constellation is an example of an existing operational MSS system that operates in the same band that is also allocated for AeroMACS [22]. Chapter 8 provides an extensive coverage on the subject of AeroMACS interference to coallocated applications. As of 2014, there were 497 towered airports in the United States.

The United States airports may also be categorized as domestic and international. While international airports carry domestic flights as well, domestic airports are exclusively used for internal flights. A significant percentage of air traffic volume in international airports is dedicated to air carrier flights operating between the United States and foreign countries. International airports are among largest, busiest, and best equipped airports in terms of runways, air traffic control facilities, and landing-aid equipment. There are 153 international airports in the United States as of December 2016. Table 1.3 provides a summary of some traffic-related data, as well as landmass sizes, for the top ten busiest U.S. international airports. Airport ranking is based on the total number of aircraft operations (landing and takeoff). The main sources for numerical data provided in Table 1.3 are FAA reports and statistical information [5], as well as individual airport traffic reports and information [23].

These airports with their landmass expanse and the volume of air traffic, as presented in Table 1.4, will require extensive AeroMACS network infrastructure containing multiple AeroMACS (cellular) base stations. The figures designated as “air carrier operations” show the number of aircraft operations related to airlines passenger flights and exclude operations related to air taxi, general aviation, and military flights. The table also provides IATA[4] airport codes (location identifier code, or station code) for these airports.

## 1.8 The Next Generation Air Transportation Systems (NextGen)

Early on in the twenty-first century, both in the United States and the European Union, long-term initiatives were taken for implementation of advanced air traffic management to support enhanced safety, increased capacity, and efficiencies of the air transportation system. In the United States, the initiative is termed the Next Generation Air Transportation

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[4] IATA (International Air Transport Association) code is a three-letter code used for identification of many airports around the world.

**Table 1.4** Air traffic information for top ten busiest U.S. international airports.

| Airport | Location | Total no. of passengers served | Total air carrier operations | Total aircraft operations | Approximate land size ($km^2$) |
|---|---|---|---|---|---|
| Hartsfield–Jackson (ATL) | Atlanta, GA | 101,491,106 [22] | 780,326 | 882,497 | 19.02 |
| O'Hare (ORD) | Chicago, IL | 76,949,336 | 597,750 | 875,136 | 29.14 |
| Dallas Forth-Worth (DFW) | Arlington, TX | 65,712,163 | 506,095 | 681,261 | 69.67 |
| Los Angeles (LAX) | Los Angeles, CA | 74,937,004 | 570,445 | 654,501 | 14.64 |
| Denver (DEN) | Denver, CO | 54,472,514 | 424,930 | 547,648 | 139.99 |
| Charlotte Douglas (CLT) | Charlotte, NC | 44,876,627 | 363,667 | 543,944 | 24.28 |
| McCarran (LAS) | Las Vegas, NV | 37,687,870 | 349,606 | 524,878 | 11.34 |
| John F. Kennedy (JFK) | New York, NY | 56,827,154 | 407,460 | 446,644 | 19.95 |
| Sky Harbor (PHX) | Phoenix, AZ | 44,006,205 | 360,675 | 440,411 | 12.14 |
| San Francisco (SFO) | San Francisco, CA | 50,067,094 | 354,576 | 430,518 | 19.82 |

System (NextGen) and in Europe it is called Single European Sky ATM Research (SESAR). Both initiatives are quite similar in what is planned to be achieved. We discuss NextGen concept exclusively, with the understanding that SESAR project shares, more or less, the same goals and plans to modernize the air transportation system. In fact, AeroMACS can be considered as a component of both NextGen and SESAR visions.

In 2003, the U.S. Congress passed the "Vision 100 - Century of Aviation Reauthorization Act," which authorized the creation of Joint Planning and Development Office (JPDO) within the Federal Aviation Administration to manage work related to the creation of a next generation air transportation system. *"JPDO has responsibility for coordinating the research efforts of its government partner agencies which include the Departments of Transportation (DOT), Commerce (DOC), Defense (DOD), and Homeland Security (DHS); the FAA; the National Aeronautics and Space Administration (NASA), and the White House Office of Science and Technology Policy, to coordinate funding with the Office of Management and Budget. Additionally, JPDO has responsibility to consult with the* *public; to coordinate federal goals, priorities, and programs with those of aviation and aeronautical firms; and to ensure the participation of stakeholders from the private sector, including commercial and general aviation, labor, aviation research and development entities, and manufacturers. JPDO is jointly funded through FAA and NASA*" [24].

### 1.8.1 The NextGen Vision

In January 2004, the DOT announced the plan for the Next Generation Transportation System as a multiagency, multiyear modernization of the air traffic system. More specifically, NextGen is a U.S. government-sponsored program aimed at modernization of NAS by means of a multistage implementation plan across the United States between the years 2012 and 2025 to meet the challenges and the goals of national and global aviation in the twenty-first century, to enhance safety and security of flights and airports, and to reduce flight delays and the negative environmental effects of aviation.

In a similar fashion, the European Union has put in place a program known as the Single European Sky ATM Research in anticipation of growth in air traffic volumes that will far outstrip the capacity of existing ATM systems. The crux of the NextGen and SESAR idea is the transformation of ATC system from the traditional radar-based system to a satellite/GPS-based radio communication network. GPS technology will be exploited for shortening the aviation routs, improving the traffic-handling capacity of the NAS, increasing the safety margin for air traffic controllers by monitoring and managing the aircraft movement, reducing flight delays and fuel consumption, and so on.

In the meanwhile, the United States and the European Union are closely cooperating to ensure interoperability and harmonization between NextGen and SESAR. These efforts are, in part, in support of ICAO GANP with Aviation System Block Upgrade (ASBU) program [25]. NextGen and SESAR projects have recognized the necessity of integration of air and ground components of the traffic management system, and the need for harmonious sharing of accurate information. In this manner, the United States–European Union joint harmonization work facilitates global modernization and advancements in air transportation systems and supports cooperation, clear communication, unified operations, and optimally safe practices [26].

### 1.8.2 NextGen Key Components and Functionalities

NextGen (as well as SESAR) is not a single program, but consists of a series of initiatives. The NextGen (SESAR) project has several recognizable components. In what follows, some major components of NextGen are briefly described.

1) A key GPS-related component of NextGen is *automatic dependent surveillance–broadcast* (ADS–B). As the name implies, this constitutes the surveillance component of the NextGen CNS. ADS-B broadcasts information on precise aircraft location to network of ground stations (air traffic controllers) and pilots using GPS–satellite technology. In the legacy NAS this type of information is provided by radar-based systems, which cannot match the accuracy afforded by GPS by any stretch of imagination. Thus, ADS-B presents a paradigm shift that essentially transforms the NAS into a more efficient one by replacing ground-based radar systems with satellite/GPS technology. The ADS-B on-board system operates by receiving satellite signal from the aircraft GPS receiving device and combining it with additional data furnished by other aircraft avionics, thereby providing a very accurate data on aircraft's location, altitude, ground speed, and many other quantities. This data is then broadcast to ground stations, aircrafts, and any other entity in the area that has proper receiving system in place. ADS-B also provides traffic and weather information directly to the cockpits of aircrafts that are equipped properly. This clearly raises the situational awareness for the pilot, in particular, and for the NAS, in general. ADS-B functionalities are divided into "ADS-B In" and "ADS-B Out." ADS-B Out provides capabilities related to broadcasting of critical flight data such as aircraft location, ground speed, and altitude. On the other hand, ADS-B In functionalities will provide the aircraft cockpit display with real-time information on traffic and weather conditions. While ADS-B In is considered to be an optional capability, the FAA requires that aircraft operating in the U.S. NAS must be equipped with ADS-B Out on-board system by January 1, 2020. According to FAA, as of October 2016, more than 24,000 general aviation aircrafts and 720 commercial aircrafts have been equipped with ADS-B Out avionics [27]. ADS-B consists of four independent components.
   - ADS-B is a satellite-based technology, the GNSS[5] Satellite Constellation is exploited for aircraft onboard GPS device to continuously receive data. This data is interpreted and sent to ADS-B ground stations.
   - Ground stations form the second component of ADS-B concept. FAA plans to install at least 700 ground stations in the United States

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[5] GNSS (global navigation satellite system) refers to a satellite-based navigation system with global reach. As of December 2016, the U.S NAVSTAR Global Positioning System (GPS), the Russian GLONASS, and the E.U. Galileo are the only operational GNSSs in the world.

that receive satellite data and transmit the data to air traffic control stations.

- Instrument flight rules (IFR) Certified Wide Area Augmentation System WAAS is required in the onboard aircraft avionics for ADS-B to function.
- For aircraft flying above 18,000 feet a 1090 MHz, extended squitter link with a Mode-S transponder is required. For aircraft flying below 18,000 feet (mostly general aviation), a 978 MHz UAT (Universal Access Transceiver) system is needed. In both cases, the additional devices are for use with an existing transponder.

2) *Next Generation Data Communication*, often referred to as *Data Comm*, is another major component of NextGen that corresponds to the communications module of the NextGen CNS. Data Comm defines a new method for pilots and controllers to access and communicate data, that is, via digital communications techniques, while currently push-to-talk voice communications is the predominant mode of information exchange. Specifically, Data Comm enables the transfer of clearances, approach procedures and instructions, all other routine pilot-to-controllers and controller-to-pilot exchanges, as well as advisories in digital communications form, predominantly in the form of text exchange. For instance, using Data Comm air traffic controllers and pilots can communicate through computer text messages instead of voice communications, which enables rapid and unambiguous (accent-free) communication of critical information such as clearance information, on the one hand; and more efficient use of available spectrum, on the other hand [28]. The schedule for Data Comm rollout is still in planning stages. The FAA is in collaborative talk with airports and operators to work out the details. However, it is believed that by 2020 the infrastructure for Data Comm will be in place and aircraft will be equipped with required onboard devices by then, as well.
3) The digital data distribution backbone of NextGen is *System Wide Information Management* (SWIM). SWIM, in effect, is an information management infrastructure that combines existing and new information systems and applications that interact through SWIM services. SWIM can be viewed as a means of providing user's access to NAS database, through either subscription or publication. The primary objective of SWIM is to provide the right information to various constituencies when needed. SWIM connects producers and users of data in a near real-time fashion with a common language and single point of contact to access data such as aeronautical information, flight information, and weather condition information [29].
4) *Performance-based navigation* (PBN) uses satellite-based navigation system, as well as onboard devices for selection of optimum and safe

routs. This clearly serves as the NextGen's CNS navigation module. PBN enables the aircraft to utilize navigation procedures that are more accurate than ground-based standard navigation aids, for more direct and shorter flight routes from departure to arrival. Consequently, PBN saves time and fuel, and therefore reduces the negative environment effects of aviation and provides more overall time efficiency. PBN also allows the realization of closely spaced parallel routs [30].

5) It is well known that substantial percentage of flight delays are caused by inclement weather and turbulent skies. The Next Generation Network Enabled Weather (NNEW) will be employed in the NextGen to significantly reduce weather-related delays. NNEW vision aims at combining weather forecasting models, climate observations, and data from airborne, land-based, and marine sources into a single national (or global) weather information system that becomes available to all NAS constituencies [31].

It should be mentioned at this point that AeroMACS, as a new broadband data link that has the ability to support the ever-expanding range of ATM communications requirements, is emerging under the modernization initiatives of NextGen and SESAR, and therefore, is considered to be an integral and enabling part of both NextGen and SESAR visions.

For a rather thorough list of NextGen components and modules, the FAA web page for NextGen [32] should be consulted. The FAA also posts progress reports and updates on implementation of various parts of NextGen on its website periodically; Ref. [27] is the most recent (as of December 2016) report.

## 1.9 Auxiliary Wireless Communications Systems Available for the Airport Surface

In addition to VHF AM radio that is available for establishing communications links between various nodes across the airport surface, there are a number of other data/voice transmission systems in place that may be used for information exchange at an airport. Some of these systems are wireless and even mobile, while the others are fixed and wired. The airport surface fiber-optic and copper cable loops are examples of wired transmission systems that support flight security and safety. These systems are parts of airport information exchange infrastructure. In Section 1.10.1, fiber-optics cable loop system is explored. In this section, some wireless communication systems that are available for use on the airport surface are briefly reviewed.

### 1.9.1 Public Safety Mobile Radio for Airport Incidents

Public safety (PS) mobile radio systems play a critical role in providing effective response to emergency situations and in the events of catastrophic man-made and natural disasters. The key challenge of disaster management is the minimization of the impact to individuals, assets, and the environment. In order to coordinate the relief efforts and to develop situational awareness, it is essential that the first responders be able to exchange voice and data in a timely manner. The PS communications system may be used at airports in case there is an unforeseen incident, or a catastrophic natural and/or man-made event, at the airport surface. The key advantage of this medium is the possibility of interoperable communications with first responders such as law-enforcement agencies, fire departments, paramedics, ambulances, and so on. In what follows, the PS communications systems, which is currently undergoing rapid expansion and evolution toward a network-centric broadband system in the United States, is briefly explored.

#### 1.9.1.1 Public Safety Communications (PSC) Systems Architecture and Technologies

The architecture for PSC has been conventionally similar to that of "precellular" mobile communications (see Chapter 2) that may be viewed as a "single-cell" system where mobile users connect to a single high-power base station that provides radio coverage to a large zone. However, new systems for the first responder are being developed and deployed that commensurate to various environments, identified by the Department of Homeland Security.

In recent years, PSC community has witnessed increased attention. This is primarily due to better awareness of the need for reliable communications for the first responders in emergency situations, particularly in the aftermath of September 11 terrorist attack on New York City and hurricane Katrina's assault on New Orleans. Hence, wideband communications technologies capable of providing services such as image transfer, video streaming, geolocation, and so on have been promoted for PS applications.

In the United States, Project-25, also known as P-25 and APCO-25 (Association of Public-Safety Communications Official International), is the dominant narrowband standard for digital wireless communication that is used for PS applications. APCO-25 is essentially a suite of communications standards used by federal, state, and local PS agencies in the United States and Canada. APCO-25 has been developed, in collaboration with TIA (Telecommunications Industry Association), with four objectives in mind. The primary objective was to improve spectrum efficiency in comparison with the legacy analog FM land mobile radio (LMR) networks.

Secondly, it was to provide enhanced equipment functionalities; third, to offer open system architecture to promote competition between various vendors; and finally, to allow effective, efficient, and reliable intra-agency and interagency communications [33].

APCO-25 continues to be a dominant PSC technology in the United States, as well as several other parts of the world, in part because of its adaptability to the changing user's need. Phase I of P-25 features radios with 12.5 kHz bandwidth capable of operating in analog, digital, or mixed modes. Phase II of Project-25 features radios operating with 6.25 kHz bandwidth, which was developed in anticipation of the FCC's narrowbanding mandate [34]. It should be noted that APCO-25 is a noncellular narrowband trunked communications network that requires a fixed infrastructure. APCO-25 provides voice and limited data communications at rates up to 9.6 Kbits/s. APCO 25 offers a rich set of services, including messaging, group calls, broadcast call, and others, through a simple and direct device-to-device "walkie-talkie"-type radio, over short range of about 5 miles [33].

Similarly, in most parts of Europe, TETRA (Terrestrial Trunked Radio) is the leading PS communications technology. TETRA, which was deployed for the first time in 1997, is a telecommunications standard for private mobile digital radio (PMDR) systems developed and commercialized by European Telecommunications Standards Institute (ETSI) to meet the needs of PS communications users in Europe [33]. Later version of TETRA known as *"enhanced packet and data service TETRA Release 2,"* referred to as "TEDS," was published by ETSI that provides enhanced packet and data service with data rate up to 473 Kbits/s [35]. TETRA is also a narrowband trunk telecommunications network.

#### 1.9.1.2 Public Safety Allocated Radio Spectrum

Several bands of frequencies are allocated for PS communications. In fact, the available spectrum for PSC is rather vast and is scattered across the RF spectrum and includes VHF, UHF, and C-band spectra. Traditionally, the UHF "800 MHz band" has been home to three applications: commercial cellular phone, private mobile radio such as SMR (Specialized Mobile Radio) and ESMR (Enhanced SMR), and PSC. Segments of the 800 MHz band have been the primary spectral bands for narrowband PSC as the main means of effective communications between dispatchers and their corresponding first responders, or between the first responders themselves. One issue of concern for PSC systems operating in 800 MHz band has been the increasing levels of interference from commercial cellular radio and private/professional mobile radio (PMR) systems operating in the same band. The interference problem in the 800 MHz band is caused by adjacent channel interference of fundamentally incompatible communication technologies. On the one hand, commercial mobile wireless systems conforming to cellular architecture, that is, multiple cells with low-power base station antennas, and on the other hand, noncellular PSC systems using a single base station with high-power antennas within a desired coverage area are mixed with spectral proximity. To combat the effects of this harmful interference, the FCC has ordered a reconfiguration, "rebanding", of the 800 MHz band, moving PS licensees to lower segments of the band and commercial cellular networks to higher segments, separated by an expansion band and a guard band [36]. Table 1.5 presents various spectral bands allocated for PSC, along with some characterizing notes for each band and their FCC designated allocation and application.

In 2002, the FCC allocated 50 MHz of spectrum, known as 4.9 GHz band, for fixed and mobile services excluding aeronautical applications. 4.9 GHz band may be used to support PSC. The stipulation is that nontraditional PS entities, such as utilities and the Federal Government may enter into sharing arrangements with eligible traditional PS agencies to use the band in support of their missions regarding homeland security.[6] One issue with this relatively new PSC band is the short wavelength of the signal that bears rapid attenuation. Consequently, this band may be suitable for PS services that require extensive bandwidth, but not practical for wide area coverage.

#### 1.9.1.3 700 MHz Band and the First Responder Network Authority (FirstNet)

Certain segments of the 700 MHz band are allocated for PSC and the remaining spectrum is assigned to commercial wireless communication systems. Signals over this band, relative to higher frequency bands, can penetrate buildings and walls rather easily, and for less obstructed terrains, they can provide coverage to large geographical areas.

In July 2007, the FCC issued an order that would allow PSST (Public Safety Spectrum Trust) Corporation to enter into leases of spectrum usage rights with commercial licensees/operators of the so-called 700 MHz "D Block" (758–763 MHz/788–793 MHz). A Second R&O (Report and Order) included rules for the D Block auction winner(s) to build a nationwide PS-shared wireless broadband network that would be paid for by the networks and not by the PS community or the taxpayers. The FCC rules are intended to ensure that PS will have priority access in emergencies and that the network would be continually refreshed with the latest technical improvements.

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[6] http://www2.fcc.gov/pshs/public-safety-spectrum/4-9GHz-Public-Safety-Band.html.

**Table 1.5** Allocated spectral bands for PS communications.

| Spectrum | Notes/PS bandwidth | Band designation | FCC main allocation/ application |
|---|---|---|---|
| 25–50 MHz | Nontrunked, susceptible to “skip interference”/6.3 MHz | VHF low band | Private land mobile state Highway patrol |
| 138–144 MHz<br>148–174 MHz | Narrowband PS spectrum, less affected by skip interference and noise/ 3.6 MHz | VHF high band | Private mobile radio |
| 450–460 MHz | Narrowband PS spectrum, virtually immune from skip and environmental noise interferences/3.7 MHz | UHF band | Land mobile radio and PS |
| 470–512 MHz | Currently used in 11 US metro areas to support critical PSC/42 MHz | T-band | The FCC is to auction off this band during 2021–2023. |
| 758–763 MHz/<br>788–793 MHz<br>“D-Block” | Allocated for a nationwide broadband PS network (FirstNet)/10 MHz | 700 MHz band | PS/commercial wireless |
| 763–768 MHz<br>793–798 MHz | Broadband PS systems: FirstNet, guard bands are provided/10 MHz | 700 MHz band | Land mobile PS/ commercial wireless |
| 768–769 MHz<br>798–799 MHz | Guard band/2 MHz | 700 MHz band | PS/commercial wireless |
| 769–775 MHz<br>799–805 MHz | Narrowband PS systems/ 12 MHz | 700 MHz band | Land mobile PS/ commercial wireless |
| 806–809 MHz<br>851–854 MHz | NPSPAC band, local, state and regional PS use/6 MHz | 800 MHz band | Land mobile PS/ PMR/cellular phone |
| 809–815 MHz<br>854–860 MHz | National PS band/10 MHz | 800 MHz band | Land mobile PS/ PMR/cellular phone |
| 815–816 MHz<br>860–861 MHz | Expansion band may be used PS/2 MHz | 800 MHz band | PS/PMR/cellular phone |
| 816–817 MHz<br>861–862 MHz | Guard band 2 MHz of bandwidth | 800 MHz band | PS/PMR/cellular phone |
| 4.94–4.99 GHz | Supports broadband applications for homeland security missions/50 MHz | 4.9 GHz C-band | WLAN, mobile data VoIP; and hoc Nets |

### 1.9.2 Wireless Fidelity (WiFi) Systems Applications for Airport Surface

Local area networks (LAN) are computer networks that provide device connectivity within a limited area, such as inside a single building or a group of buildings. In order to extend the outreach of a LAN, it can be connected to other LANs over any distance to form a larger telecommunications network. Several different transport protocols can be adopted for a LAN infrastructure, which includes Ethernet, token ring, ATM, frame relay, and so on. The adopted networking technology determines which data transmission methods can be implemented and defines the maximum possible transmission speed (maximum data rate and throughput). Therefore, the selection of the networking technology is a critical design matter that influences the capabilities and capacity of the LAN.

The Wireless Fidelity (WiFi) technology is an IEEE 802.11 Standard-based wireless alternative to wireline LAN. Originally, this wireless local area network (WLAN) was developed as an extension of Ethernet over license-free ISM (industrial scientific medical) bands, primarily, for private applications. However, WiFi has gradually become commonplace in public locations for creation of so-called "hot spots," offering the user easy, and often free-of-charge, broadband access to the Internet [37]. In order for WiFi technology to become as commonplace as it is today, the technology had to address four major technical challenges. Simplicity of operation and use has been always paramount for any publicly used electronic system. The second issue is the security and interference over ISM bands. Resource planning and bandwidth allocation cannot be guaranteed over ISM bands, and essentially there are no protections against interference, aside from the fact that FCC limits the output power of the systems that might operate over these bands. For instance, the domestic and commercial (restaurant) microwave ovens operate near 2.45 GHz, this is within the most popular ISM band of 2.4–2.5 GHz.

The current state of the art of WiFi technology allows pleasure and business travelers to continually stay connected through WiFi networks in their residences, restaurants, airport waiting halls, and on aircraft. It is also possible to acquire a cost-effective and convenient global WiFi access across smartphones, tablets, and laptops. By the year 2018, it is estimated that on average, there will be one WiFi hot spot for every 20 inhabitants of the planet. In 2014, 52% of the global IP traffic was carried through wireline networks, 44% via WiFi devices, and cellular phones' share only accounted for 4% of this traffic. It is expected that the WiFi proportion of traffic for Internet access will increase in the future [38]. The WiMAX networks may be used to provide backhaul[7] support for mobile and stationary WiFi hot spots. Originally, WiFi hot spots were connected to the Internet via a wireline backhaul networks such as digital subscriber line (DSL). However, by using a wireless backhaul network such as WiMAX, the costly wireline infrastructure can be avoided [39].

WiFi technologies have several categories of applications in air transportation systems, in general, and in the airport area, in particular. One is a commercial application that provides broadband Internet access to passengers, crew, and airport labor forces, within the airport waiting halls, gate areas, and even inside the aircraft while it is parked in front of a terminal gate. This service is provided to the users free of charge in large percentage of United States and international airports. WiFi services are also commonplace aboard aircraft, providing broadband IP access to passengers while the aircraft is in flight.

The WiFi hot spots, distributed on the surface of airports, a “WiFi system”, may be viewed as an ancillary wireless network that might be applied to support, or provide backup support, for some aviation functionalities. For instance, Ref. [40] describes an interesting application of WiFi networks in positioning system, considered as an alternative to that of GPS-based system. The article introduces an approach for automatically calibrating the WiFi positioning system to improve accuracy and to achieve performance levels that are comparable to those of GPS system. A prototype of this system has been implemented and tested in Munich airport in Germany. It is anticipated that WLAN applications, in various aspects of air transportation systems, will expand in the future.

## 1.10 Airport Wired Communications Systems

The current wired airport surface communications system primarily consists of buried copper or fiber-optic cables. The principal purpose of the airport cable system is to provide the physical media that enables interconnectivity of all communications systems and “communications rooms” across the airport. In this section, we briefly explore the dominant wireline signal exchange media on airport surface, that is, the fiber-optic cable loop communications systems (CLCS).

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[7] Backhaul networks are intermediate networks that provide connection between the core (backbone) networks and the small subnetworks that need to access the core network. In this case, the backbone network is the IP network and subnets are WiFi hot spots, and WiMAX as a backhaul network connects the WiFi hot spots to the IP core network for Internet access.

In late 1980s, the FAA initiated a modernization plan by introducing fiber-optic technology to airport surface communications, a technology that is still the dominant mode of information exchange on the airport surface. The fiber-optic transmission system is complemented by VHF radio for point-to-point transmission, as well as by airport auxiliary communications networks; hence, in fact, a hybrid communications approach is in place. The fiber-optic cables interconnect the air traffic control system to communications, navigation, and surveillance facilities, as well as to other airport constituencies. The goals for this modernization were stated to be increasing the capacity of the NAS, improving the safety of airspace operations, increasing the productivity of FAA facilities, and enhancing the overall cost effectiveness of the NAS operations [41].

Employing fiber-optic cable loop enables simultaneous bidirectional signal transmission using multiple fiber strands in the cable. This provides redundancy and enhances reliability. Additionally, a number of benefits are realized when the backbone of airport surface communications infrastructure is fiber optics, simply because the information is transported via optical signals. A partial list of these benefits is provided further.

- *Extremely High Bandwidth:* Single-mode fiber-optic cables can carry signals at speeds in excess of 1 Tbps.
- *Immunity to Electromagnetic Interference:* Since the signal is carried by light, fiber-optic cables are immune to electromagnetic interference.
- *Low Signal Loss:* These cables induce very low loss as optical signal travels through. For instance, a cable specified by FAA for use in airport circuits, FAA-E-2761a, has signal loss as low as 1 dB/km [39]. However, in modern single-mode fiber-optic cables, the typical loss is less than 0.3 dB/km. For this reason, single-mode fiber-optic cables can sustain transmission over distances of up to 140 km before regeneration is needed [41].
- *Electrical Isolation of Transmitter from the Receiver:* This simplifies link design as there are no ground loops.
- *Small Physical Size and Weight:* Cables containing six fibers in protective jackets can be as small as one half of inch in diameter [41]. In today's state-of-the-art fiber-optics technology, a fiber cable may contain up to a thousand fiber strands.
- *Security and Cross Talk:* There is no signal leak out of a fiber optic, consequently no cross talk between the fibers or fiber-optic cables exists [42].
- *High Electrical Resistance:* Fiber cables are not affected by close by high-voltage equipment. In fact, fiber-optic cables for airport surface communications are buried with power cables in the same trenches [41].
- *Wavelength Division Multiplexing* (WDM): For duplex communications, fibers are normally used in pairs, with one fiber carrying the signal

in one direction and the other in the opposite direction. However, simultaneous transmission of several signals over a single strand is possible by using different wavelengths and appropriate coupling/splitting devices. This is the essence of wavelength division multiplexing that enables a single-fiber strand to bear an aggregate data rates measured in terabits per second.

Some of problems and disadvantages of utilizing fiber optics for data transmission, in general, and for airport surface communications, in particular, are discussed further.

- *High Installation Cost:* The initial investment for installation of fiber-optic infrastructure is still high, although these costs are dropping significantly every year. It should be noted that despite significant initial expenses, over the lifetime of fiber-optics communications system, they prove to be more economical than similar wired electrical transmission systems, that is, they are of lower cost in the long run.
- *Optical Transmitters and Receivers:* The optical transmitter/receiver systems are more expensive than those of electrical systems that are used for the likes of coaxial cables.
- *Susceptibility to Physical Damage:* Fibers are compact and tiny transmission media (on the order of few to around 100 μm in diameter[8]) and are highly susceptible to getting cut, broken, or damaged during installation or construction activities.
- For the case of airport surface communications, an additional challenge crops up when the cable network needs to be repaired, upgraded, or expanded. Since cables are installed underneath the airport surface, it may be required that a section of the airport surface be blocked and be placed out of service temporarily. This could cause the shutdown of some airport runways and taxiways, which translates into lower capacity, airport congestion, and loss of revenue. This is one of the reasons that a network-centric wireless standard, such as AeroMACS, is preferred for airport surface over CLCS.

Fibers are made out of either glass or transparent plastic; however, for long-distance communications, glass fibers are used exclusively owing to lower optical absorption in glass fibers.

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[8] Normally, the diametric size of an optical fiber is given by three numbers that represent the outer diameter of the core (central part of the fiber through which light is transmitted), diameter of core and cladding (an outer layer glass that facilitates the transmission of light down the fiber), and diameter of core and cladding and coating (multilayers of plastic applied to provide protection against shocks and from abrasion) put together, respectively. For instance, by fiber size of 100/150/250, it is meant a fiber with core diameter of 100 μm, cladding diameter of 150 μm, and coating diameter of 250 μm.

### 1.10.1 Airport Fiber-Optic Cable Loop System

Fiber-optic cable loop system provides interconnectivity between the "communication rooms" through cabling routed between each of the "rooms" that are distributed throughout the airport's area, and from the communications rooms to the users' workstations. The communications rooms serve as the distribution points for the end users of various airport systems [43]. The phrase "loop system" means a closed-loop transmission system that provides an inherent redundancy in the event of any single link being detached from the loop. Fiber-optic loop systems have an additional advantage of simplicity, in that they can be implemented using as few as only a pair of fibers, whereas traditional copper cable loops require multiple pairs of facilities [41].

Two basic configurations are defined for loop systems. The simplest one is when a loop is shared by only two facilities, and the second is when the number of facilities connected to the loop is at least three. A loop that is shared by three or more facilities must have a protocols suite designed to manage the operation of the loop, for determining which node is allowed to receive or transmit at any given time, while preserving the integrity of the transmitted data. For airport fiber-optic loop systems, two protocol suites have been recommended, time division multiplexing (TDM), where all facilities have equal and orderly access to the loop, and fixed master–slave protocol (MSP) with multiple slaves, where a slave is addressed and responds according to a predetermined procedure [41].

The airport facilities, such as ATCT, ASR (airport surveillance radar), security devices, various remote transmitters and receivers, and so on, are distributed across the airport area according to the initial installation and the airport ensued evolutionary development path. In MSP, each node receives all the transmitted data on the loop, but accepts and reacts only to the information addressed to it [41]. The operation of a MSP using counter-rotating rings[9] proceeds as follows:

- The ATCT, which plays the role of master, transmits interrogation and command signals into the loop. The signals are received by a facility, that is, a slave, regenerated and transmitted to the next facility in the loop.
- The signals typically consist of a facility address code followed by the message for that facility. A facility's response to an ATCT interrogation takes the form of an immediate message into the loop. When the ATCT has received a response, it repeats the sequence until all facilities have been interrogated and have responded.

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[9] In counter-rotating ring configurations, there are two rings in use. One ring transmits in a clockwise direction, while the other transmits in a counterclockwise direction. This provides a fully redundant system that is unaffected by a single failure in either loops.

- If a facility fails to respond within a prescribed time and after a predetermined number of polls, diagnostic operations are initiated at the ATCT to determine the failure mode. When a message becomes distorted during transmission, a request to retransmit will be generated.
- The ATCT receiving device is configured to prevent retransmission of signals.
- Both the clockwise and counterclockwise transceivers receive signals from their respective directions, and in turn, they retransmit the signals. Although the two signals are identical, they are not synchronous at any given facility because the lengths of the transmission paths are different. Therefore, some accommodation is necessary, using one of two methods. One is to correct for the difference in arrival times. The other method is to preferentially accept either of the two signals based on a criterion such as signal quality or some other predetermined preference, or a combination of the two methods.

As far as optical network architecture is concerned, the loop configuration is based on synchronous optical network (SONET) ring architecture. SONET defines optical signals and synchronous frame structure for multiplexed digital traffic [42].

### 1.10.2 Applications of CLCS in Airport Surface Communications and Navigation

Currently, the fiber-optic CLCS supports a number of applications on the airport surface. As was mentioned earlier, the fiber-optic cable loop, primarily, forms the backbone of communications and information exchange for various airport functionalities supporting voice/data/and video services. The loop system also distributes voice and video signals across the airport terminal field.

The second category of services supported by fiber-optic CLCS is in airline and airside[10] operations, and in aircraft and passenger's operations through the airport's airside. These services include FAA air traffic control and Navigation Aids (NAVAID) systems, aircraft refueling, visual docking guidance, runway monitor, gate management, parking information, baggage handling, and so on.

Airport landside operations comprise all essential services needed to support operations for travelers, luggage, and cargo to and from the

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[10] An airport is divided into two areas of landside and airside. Airport spaces related to physical access to the airport, such as access roads, parking decks, and train stations are called landside areas. Airside areas are airport locations that are accessible to aircraft, such as runways and taxiways. Airside operations consist of ramp control, aircraft gate control, and access control.

ground transportation. These services include but are not limited to parking systems, taxi dispatch, and surface vehicle monitoring. Fiber-optic CLCS supports these services as well.

Another airport operation supported by fiber-optic CLCS is in airport safety and security operations. Security systems include fire alarms, explosive detections, perimeter sensors, close circuit television (CCTV), access control, and so on [43–44].

## 1.11 Summary

In this chapter, the evolution of airport wireless communications systems from the legacy analog VHF AM system to the making of the AeroMACS concept, is sketched. The background material that explains the reasons behind the emergence of this innovative aviation technology is described. The technical details of AeroMACS networks are covered in the following chapters. AeroMACS will operate within the larger context of NAS, as well as in the International Airspace System. A concise overview of the current NAS is presented. The Federal Aviation Administration's NextGen vision, planned to transform and modernize the NAS, is discussed in some details. NextGen promises to vastly improve the precision of aircraft navigation, enhance the quality of aircraft position data that is made available to controllers, and reduce the burdens of air-to-air and air-to-ground communications. The emergence and evolution of pre-AeroMACS digital communications techniques in aviation are discussed. ACARS and VDL technologies are briefly reviewed. The major technologies that currently play complementary and auxiliary roles to VHF radio and fiber-optic loop in the airport communications infrastructure are discussed. The airport fiber-optic cable loop system is briefly reviewed. It is pointed out that although communications networks based on fiber optic cable buried underneath the airport area are available in the majority of the U.S. airports, they are found to be expensive to install and maintain. In addition, repairing, upgrading, and updating fiber-optic cable system is a challenging task that may require blocking a section of the airport surface and putting it out of service temporarily. The Aeronautical Mobile Airport Communications System overcomes some of the challenges associated with the fiber-optic cable loop system.

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