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Current Communication Radio Systems for Data Link

1.1. History and definition

1.1.1. *From voice to data link*

The earliest communication with aircraft was by visual signaling using, for instance, colored paddles or hand signs. This communication means was mainly dedicated to ground crew but was not suitable for pilots. The first aeronautical radio link for air–ground communications was proposed at the beginning of the 20th Century. The first radio transmitter was invented and tested by AT&T in 1917. This allowed for the first time voice communications between ground personnel and pilots. After the First World War, new radio communication systems offering greater range and better performances were developed. But, it was only in 1935 that airborne radios were considered reliable and efficient enough to be widely deployed on existing aircraft.

These air–ground communication means were proposed in order to increase air safety. In the years that follwed, the Very High Frequency (VHF) band was mainly used for radiotelephony services between pilots and controllers. Even though the used technologies have, of course, evolved, the main principle is still the same today: the VHF-reserved bandwidth (today from 118 to 137 MHz also known as aircraft band or airband) is split into several channels with a spacing to ensure efficient sharing of resources. First, implementations were based on 140 channels with a spacing of 100 kHz. From 1979 to 1989, the bandwidth was split into 760 channels with a spacing of 25 kHz. And at the end of the 1990s, digital radio was introduced and greatly increased capacity by reducing the bandwidth required for speech transmission. Then, the airband (117.975–137 MHz) was split into 2,280 channels with a spacing of 8.33 kHz. In order to ensure the required availability, a voice communication uses either VHF or high frequency (HF) (from 3 to 30 MHz) voice radios. It has been further augmented with Satellite Communication (SATCOM) since the early 1990s. Hence, voice communications are possible even in oceanic areas where direct communications with VHF ground stations cannot be deployed due to their range.

Nevertheless, considering the increasing number of aircraft in the airspace at the same time, the lack of resources makes it necessary to first seek new solutions in order to avoid congestion. An innovative solution, known as data link or digital data link, is based on new solutions and ways to exchange between end users. Data link offers the ability to transmit short and relatively simple digital messages between aircraft and ground stations via communication systems that are today more often based on VHF or SATCOM. It was at the end of the 1970s that airlines were convinced by the advantages of communications based on data link. In July 1978, the engineering department at Aeronautical Radio Incorporated (ARINC) introduced the first data link means known as Aircraft Communications Addressing and Reporting System (ACARS). The objectives of this new way to communicate were to reduce crew workload and improve data integrity. This system, also known today as Plain Old ACARS (POA) and still in use in some airspace, uses VHF channels initially dedicated to voice communication. It operates at 2.4 kbps and was first used for communications dedicated to airlines. The word ACARS also refers to the messages' format. The first application was Out, Off, On, In (OOOI) and has the aim to simplify the management of airlines crew members and particularly pilots. It allows communicating accurately and immediately when the aircraft leaves the gate, takes off, lands and so on. ACARS has been enhanced by new applications, and its use extended to other communication means such as SATCOM and HF links. And during the 1980s, air traffic control (ATC) authorities began to encourage the use of ACARS between controllers and pilots to improve the safety and efficiency of air traffic management.

It has to be underlined that the term "data link" is quite ambiguous, particularly for network engineers or researchers, as it normally refers to the second lowest layer (layer 2) in the Open Systems Interconnection (OSI) reference model stack. In the context of this book, the term refers more often to the digital message-oriented means currently proposed to communicate between aircraft and the ground, as an alternative to analog voice communications.

The combination of all the different technologies and their applications to Air Traffic Management (ATM) dedicated to air–ground communications are a part of a whole set known as Communication, Navigation, and Surveillance/Air traffic Management (CNS/ATM) systems. The CNS/ATM systems are defined by the International Civil Aviation Organization (ICAO) as “Communications, navigation, and surveillance systems, employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global air traffic management system” [ICA 02]. At the beginning of the 1980s, ICAO decided to create a special committee with the mission: “to identify and assess new concepts and technologies, which may have future benefits for the development of international civil aviation” and with the goal to define the operational concepts for future ATM exploiting the availability of digital technology. This committee is known as Future Air Navigation System (FANS). During the 1990s, Boeing then Airbus has developed their FANS product, respectively, known as FANS-1 and FANS-A. Finally, these two products are joined as FANS-1/A. Considering Data Link operation, as explained in [ICA 06] an aircraft is considered FANS-1/A equipped if it has the Air traffic services Facilities Notification (AFN) capabilities. All these successive steps from the previous century today give a heterogeneous and relatively complex aeronautical world where air–ground communications may be based on analog voice, POA, FANS 1/A or even FANS 2/B with the lastest improvements. The main objectives of this book are to clearly explain these concepts and to provide the readers some future trends with the presentation of some great projects and some research fields.

1.1.2. *Communication traffic classes*

The ICAO provides recommendations known as International Standards and Recommended Practices and Procedures for Air Navigation Services (SARPS). In the context of aeronautical telecommunications, the “Annex 10” document (volume 3, Chapter 3) [ICA 07] makes the distinction between four categories of communications. Air Traffic Service

Communications (ATSCs) and the Aeronautical Operational Control (AOC) Communications that are considered as safety related, and the Airline Administration Communications (AACs) and the Aeronautical Passenger Communications (APCs) that group non-safety-related applications as shown in Figure 1.1.

These application classes allow defining specific requirements for each application regarding the classes it belongs to and its properties:

– *ATSC, (critical)*. This class regroups communication between pilot and ATC to ensure the safety, speed and efficiency of the flight. Services can be supported by voice broadcast or data communications. For instance, these services may be related to meteorological information, route information during the flight, etc.;

– *AOC, (critical)*. According to ICAO documents, this class regroups communication required for the exercise of authority over the initiation, continuation, diversion or termination of flight for safety, regularity and efficiency reasons. For instance, it includes airline companies' communication with their aircraft (e.g. maintenance messages, fuel levels, exact departure and arrival time, etc.);

– *Airline Administration Communications (AAC), (non-critical)*. According to ICAO documents, this class regroups communications necessary for the exchange of aeronautical administrative messages. AACs are neither linked to the security nor to the efficiency of the flight. A few examples of AAC are information regarding passengers (list of passengers and connections), special cleaning requests, etc.;

– *APC, (non-critical)*. This class regroups communication related to the non-safety voice and data services to passengers and crew members for personal communication.

It has to be noted that critical communications follow very specific international rules defined by ICAO (for example, only some dedicated frequency bands can be used) particularly for ATSC and AOC and are based on dedicated systems. These latter must meet very stringent quality of service (QoS) requirements mainly based on parameters of transaction time, continuity, availability and integrity. These regulatory constraints do not apply to non-critical communications even if they may have to meet some requirements according to the applications (e.g. delay for passenger telephony).

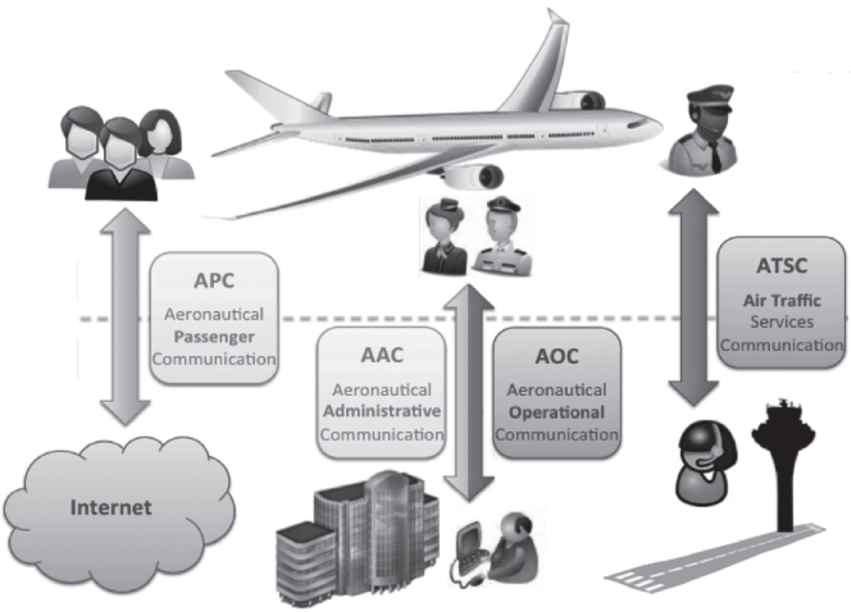

Figure 1.1. *Aeronautical communication traffic classes*

Sometimes, AAC services are included in AOC services that give only three classes: ATSC (or ATS) and AOC as safety-related classes, and APC as the non-safety class. The current solution in civil aviation communication to ensure segregation between safety service classes and APC is a physical segregation between critical communications and non-critical communication. The pieces of equipment aboard aircraft are physically different.

In this book, we will mainly focus on communication systems dedicated to critical services (ATSC and AOC).

1.1.3. *Main actors and organizations*

Many actors and organizations are involved in communication systems dedicated to data link, services design, standardization, deployment and maintenance. And different taxonomy can be proposed. As shown in Figure 1.2, we consider four classes of actors and organizations.

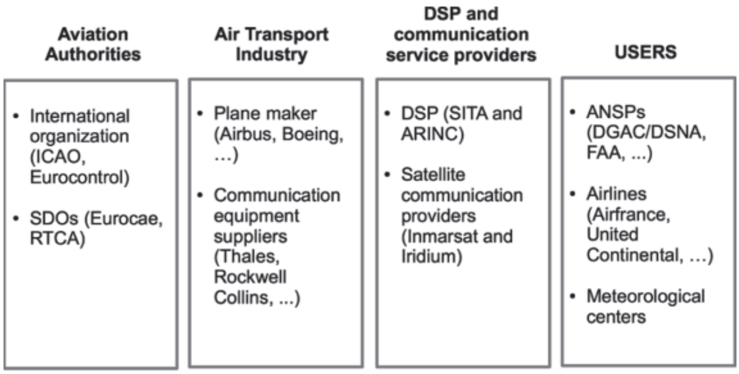

Figure 1.2. *Main actors and organization classes*

The first class includes aviation authorities. Their main objectives focus on the definition of the principles and techniques for international air navigation. They promote the planning and development of international air transport in order to ensure safe and orderly growth. The ICAO, which is certainly the most important organization of this class, is a specialized agency of the United Nations (UN). It was created in 1944 and currently consists of 191 of the 193 UN members. The ICAO Council adopts standards and recommended practices concerning air navigation, its infrastructure, flight inspection, prevention of unlawful interference and facilitation of border-crossing procedures for international civil aviation. ICAO standards are known as Standards and Recommended Practices (SARPS). Standards may also be developed and issued by government agencies or Standard-Developing Organizations (SDOs). When a standard is declared acceptable, it can be used as a standardized means. EUROCAE and RTCA are two well-known SDOs. EUROCAE certifies aviation electronics in Europe. As explained on their website, RTCA is a private, not-for-profit corporation that develops consensus-based recommendations regarding communications, navigation, surveillance and air traffic management (CNS/ATM) system issues. EUROCONTROL is the European Organization for the Safety of Air Navigation founded in 1960. It is an international organization working for seamless European air traffic management. EUROCONTROL is a civil organization and currently has 40 member states. EUROCONTROL's headquarters are located in Brussels. It coordinates and plans ATC for all of Europe. This implies working in close partnership with several organizations such as national authorities, air navigation service providers (ANSPs), civil and military airspace users, and airports.

The second considered class relates to “Air Transport Industry”. It includes the main plane manufacturers, such as Airbus or Boeing, and communication equipment suppliers. These different actors are involved in communication systems dedicated to data link in the sense that they have to design, produce and install specific equipment that is in compliance with the aviation authorities’ regulations and guidelines.

The third class relates to Data link Service Providers (DSPs) and, more broadly, communication service providers. These message service organizations are responsible for the reliability of the transmission media and the integrity of the message. The DSP is expected to create and manage the multiple data links that transmit a variety of messages related to specific applications between the aircraft and ground. It operates a network of ground stations that are generally located at airports and other sites in order to provide VHF, HF and SATCOM coverage in continental and oceanic airspaces. There are several competing DSPs in the world, in some areas with overlapping service, e.g. Europe. The two primary service providers are ARINC and SITA. SITA, originally known as the International Company for Aeronautical Communications, was founded in February 1949 by several airlines in order to define shared infrastructure by combining their communications networks. Today, SITA is a multinational information technology company specializing in providing information technologies and telecommunication services to the air transport industry. ARINC, established in 1929, is a major provider of transport communications and systems engineering solutions for different industries including aviation and airports. For instance, ARINC and SITA have deployed networks of ground stations providing VHF Data Link (VDL) mode 2 service in Europe. Aeronautical satellite services providers provide communication means based on satellite links particularly dedicated to oceanic airspaces. Satellite systems for aeronautical safety communications operate in the mobile satellite service radio frequency bands included in the L band (1–2 GHz). ICAO has identified this frequency band for Aeronautical Mobile Satellite Services (AMSSs) for ATSC. Moreover, ICAO authorizes only some satellite systems, for instance, Aero-H/H+/I/L proposed by Inmarsat or Iridium. Inmarsat operates four geostationary satellites that cover about 97% of the earth’s surface. The Iridium system is based on a constellation of 66 cross-linked satellites (plus seven spares) that create its network of global coverage.

The last class lists the users. Here we find the ANSP. ANSPs are government departments, state-owned companies or sometimes private organizations. As an example, we cite *Direction Générale de l'Aviation Civile* (DGAC, The French Civil Aviation Authority), particularly the *Direction des Services de la navigation aérienne* (DSNA) entity, in France or the Federal Aviation Administration (FAA) in the United States. The DSNA is the agency in charge of ATC, communication and information for France. The FAA is the national aviation authority of the United States, and it has an authority to regulate and oversee all aspects of American civil aviation. ANSPs belong to this class, because they are responsible for the ATC. The users' class also includes the airlines, e.g. a company that provides air transport services for traveling passengers and freight. Of course, it would be complicated and difficult to list them exhaustively, but we can cite some from the top groups by revenue: Lufthansa, United Continental, Delta Airlines, Air France KLM and FedEx. The airlines are currently users of communication systems dedicated to data link mainly for ATSC, AOC or AAC. A third subclass of users can be considered with meteorological centers that provide or collect meteorological information and produce forecasts. On the one hand, aircraft may use particular embedded equipment named Data Management Unit (DMU) equipment for acquiring data related to weather observations, e.g. temperature, wind at various positions and flight levels. This feature is performed by a number of airlines. Data are sent to international meteorological centers as input to weather forecast models. Further information on sky conditions or turbulences can be sent by the pilots during their flight in order to inform ATC, for instance. On the other hand, meteorological centers provide weather information and forecasts that can be sent to aircraft during the flight. These data are generally provided to the aircraft through particular data link applications. For instance, Significant Meteorological Effects (SIGMETs) are advisories regarding significant meteorological conditions that could affect the flight. A Meteorological Aerodrome Report (METAR) allows the pilot to get updated weather conditions and forecast at the departure and destination airports as well as at other airports along the route.

1.2. Systems architecture

1.2.1. *ACARS*

The first version of air–ground communication based on digital messages, called ACARS, was introduced in 1978 by ARINC. It aimed to improve the integrity of data exchanged with the aircraft crew and lower aircrafts' operation costs by replacing voice or hand-written and paper-based procedures with a digital message system based on the existing airline teletype system. It is described in several ARINC documents: the protocol is described in ARINC 620 (ground–ground interface) and ARINC 618 (air–ground interface), but several other documents (among others 724, 750, 635 or 619) deal with ACARS.

The term ACARS[1] refers to the complete air–ground system, and thus is used to designate different elements in an air–ground communication chain: airborne systems, the air–ground subnetwork (e.g. plain old ACARS), ground systems, the network services, the applications using the network, etc. To avoid any confusion, except for well-known denotation like POA or AOA, we will "reduce" ACARS to a network system providing air–ground communication services by using more or less dedicated air–ground subnetworks. This definition thus excludes the air–ground subnetwork, which may be used by different networks (e.g. VDL mode 2 supports both Aeronautical Telecommunication Network (ATN) and ACARS through AOA). It also excludes the applications as they obviously cannot be defined as specific to the ACARS network from an operational point of view.

Technical choices in ACARS were mainly driven by the available technologies (e.g. radio and modulation) and networks (teletype). Limiting the costs of the onboard systems led to keeping the complexity of routing in the ground-based systems. Finally, the considered communication model was limited to communication between an airline and its registered aircraft, which means that the destination could easily be determined by the aircraft address and the type of data: in this context, a ground end system destination address is not required.

As a result and compared to the networks now available, the basic ACARS network provides a low Quality of Service (QoS) communication capability, only between airline's ground-based systems and airline's aircraft, which still complies with typical airline applications requirements:

– human readable character-oriented transmissions only (like teletype);

– connectionless and unacknowledged end-to-end service;

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1 ACARS is described in several ARINC documents. The protocol is described in ARINC 620 (ground–ground interface) and ARINC 618 (air–ground interface), but several other documents (among others 724, 750, 635 or 619) are dealing with ACARS.

– no end-to-end integrity checking;

– centralized and ground-based routing;

– low to very low data rate (depending on the air–ground subnetwork used to transmit the data);

– long delays and high jitter (due to the air–ground subnetworks management);

– no security features.

The main ACARS system enhancements aimed at providing more interfaces with the onboard avionics, providing a worldwide coverage or security features and allowing sending longer messages, like in the current Media Independent Aircraft Messaging (MIAM) project.

The first air–ground subnetwork used by ACARS was VHF based. It offers 2,400 bps throughput, to be shared among the communicating stations. Due to the limited range of the ground stations, VHF ACARS only covers continental areas.

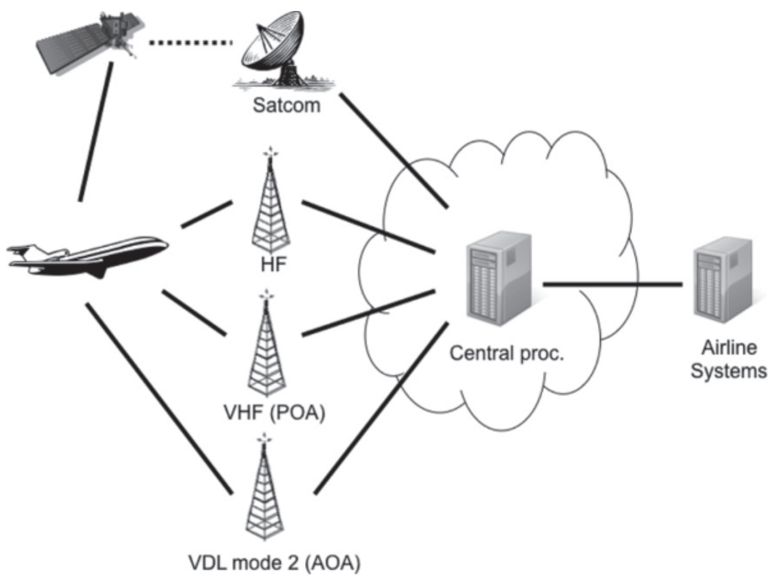

Figure 1.3. *Air–ground communication systems*

ACARS has dedicated radio channels in the aeronautical VHF frequency band. These channels are allocated on a per service provider basis in each region (e.g. Europe and US) and a single service provider may obtain several frequencies (as it is the case for SITA and ARINC, for example, in Europe) if the amount of traffic so requires.

So as to overcome the limitations of VHF ground stations' coverage, service providers proposed ACARS using geostationary communication satellites during the 1990s.

Finally, HF data link (HFDL) and other satellite constellations (lower orbits) achieved global coverage for the aeronautical industry.

1.2.2. *FANS 1/A*

Starting from the FANS special committee's satellite CNS/ATM concept, Boeing worked on the first set of applications using the then available technologies for air–ground data communications: ACARS using satellite. This project focused on oceanic and remote airspaces with no radar coverage and poor HF voice communications. The selected applications thus addressed communication and surveillance needs for these airspaces: Controller Pilot Data Link Communication (CPDLC) for controller to pilot communication enhancements, and Automatic Dependent Surveillance – Contract (ADS-C[2]) to enhance surveillance in regions without radar coverage.

CPDLC allows for the direct exchange of standardized messages between a controller and a pilot, replacing traditional voice communications that may be of poor quality with HF. In addition, it allows some automation by using and processing the exchanged data by onboard and ground systems.

ADS offers an alternative to voice position reporting in use in non-radar airspaces: aircraft using ADS-C automatically transmits reports on their position and intent to the ground control.

2 ADS Contract (ADS-C) is point-to-point based, addresses ground surveillance in regions with no radar coverage and requires the pilot to log onto the ground system, as opposed to ADS Broadcast (ADS-B) which is point to multipoint-based, addresses both air–air (e.g. situation awareness) and air–ground communication and does not require crew interaction.

FANS 1/A also includes an additional application: ATC Facilities Notification (AFN) providing LOGON functionality. This application is required in order to associate an aircraft's network address with its flight plan in the ground system.

The reduction in positioning inaccuracy that these applications achieve will later allow reducing both minimum horizontal separation between aircraft (from about 100 Nm down to 50 or 30 Nm) and pilot/controller's workload (thus increasing airspace capacity), and also flying more efficient routes for fuel consumption reductions.

These applications were designed as bit-oriented applications and their operation required a QoS that the ACARS network could not provide per se.

The features required by ATSC applications that ACARSs do not provide are the followings:

– end-to-end connection service with end-to-end error checking and acknowledgment;

– additional ground addressing feature and interconnection so that any ground ATC facility can communicate with any aircraft in its airspace (regardless of the DSP);

– a bit-to-character conversion.

The functionalities and applications presented here above are described in the ARINC 622. They are known as FANS 1/A, or sometimes Initial Future Air Navigation System and have been developed by Boeing during the early 1990s and by Airbus some years later.

The required QoS (especially concerning delays and jitter) for a data link system naturally depends on the airspace and its traffic density. They are known as RCP or Required Communication Performances and are bound to the minimum horizontal separation between aircraft. FANS 1/A has been designed for low-density oceanic or remote areas, and only satellite and VHF air–ground sub networks were initially compliant with the latency requirements of CPDLC.

In addition, it has to be noted that FANS 1/A functions have been integrated with other avionics onboard the aircraft, especially the Flight

Management Systems (FMSs), allowing the flight crew to automatically extract flight data from or load clearances into this avionics system.

Besides FANS 1/A, other ATS-related data link applications use the ACARS network.

The first set of applications is: Digital Automatic Terminal Information Service (D-ATIS), Departure Clearance (DCL) and Oceanic Clearance (OCL). D-ATIS may also be used to provide Digital meteorological information for aircraft in flight (D-VOLMET). These applications use the exact same ATSC specific features as described previously: especially end-to-end CRC and additional ground addressing. They may, however, be implemented independently from the FANS 1/A AFN, CPDLC and ADS applications. However, it has to be noted that DCL and OCL are subsets of controller-to-pilot communications, and the same operational service may be delivered through the CPDLC application.

In the USA, the pre-departure clearance (PDC) service is provided through ACARS instead of DCL. These applications have a different operational scenario and are not standardized: the PDC is first sent from the tower to an airline host computer that will forward the clearance via ACARS.

1.2.3. *ATN baseline 1 and FANS 2/B*

1.2.3.1. *ATN internetworking*

In parallel to the development and deployment of FANS 1/A, ICAO working groups continued the development of standards for a new aeronautical dedicated network and a set of applications: ATN. In addition to ground–ground applications (e.g. messaging with AMHS and ATS Message Handling System), ATN also defines air–ground data link applications, similar to those presented previously with some modifications and improvements.

As was stated in the second edition of ICAO document 9750:

"The ATN and its associated application processes have been specifically designed to provide, in a manner transparent to the end-user, a reliable end to end communications service over dissimilar networks in support of air traffic services. ATN can also carry other communications service types, such as AOC communications, AAC and APC."

ATN is a global internetwork architecture described in [ICA 10b]. As such, it relies on different "real" subnetworks, allowing interconnecting ATN routers. ATN defines a stack of ISO standardized protocols from the network layer up to the application layer, including a routing protocol, and some convergence functions aimed at adapting the network protocol to the underlying physical subnetworks, as presented in Figure 1.4.

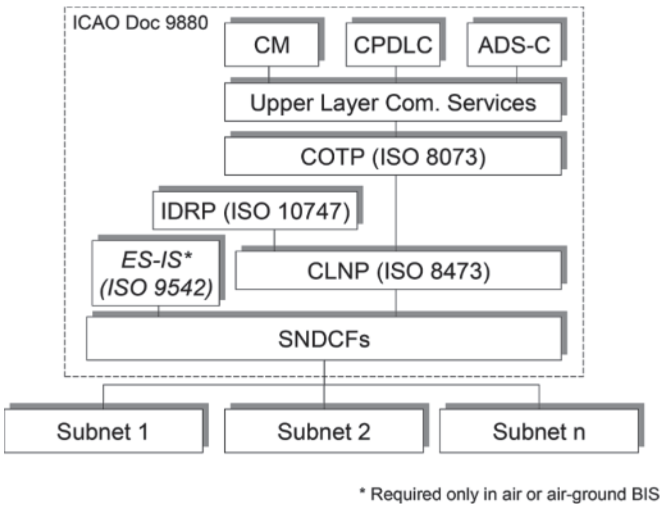

Figure 1.4. *ATN protocol stack*

ATN is based on Connection Less Network Protocol (CLNP) as defined in ISO 8473 at the network layer. At the transport layer, all the currently defined applications use Connection Oriented Transport Protocol (COTP) as defined in ISO/IEC 8073. COTP provides a reliable transport service. Provisions to use Connection Less Transport Protocol (CLTP) as defined in ISO 8602 have been introduced. [ICA 10.b] also defines some common application services for session and presentation layers and a part of the application layer, known as Upper Layer Communications Services (ULCS). The remaining part of the upper layers depends on the application itself.

Concerning routing protocols, ICAO considered that intradomain routing will be a local matter, and the choice of the related routing protocol will remain implementation specific. Thus, ATN only defines a protocol to cope with interdomain routing: Inter Domain Routing Protocol (IDRP) as defined in ISO 10747, which will be implemented in the Boundary Intermediate System (BIS) routers (i.e. at the boundary of the routing domains).

In the very specific case of air–ground data link, ATN also makes use of one PDU from the ES-IS protocol as defined in ISO 9542 in order to handle airborne router discovery between an airborne BIS and the first ground BIS (also known as air–ground BIS).

Finally, several SubNetwork Dependent Convergence Functions (SNDCFs) are described and act between the CLNP protocol and the considered subnetwork: X.25 SNDCF, IP SNDCP, etc. There is one specific SNDCF called Mobile SNDCF whose role is to deal with subnetworks of an aircraft (e.g. VDL mode 2).

ICAO working groups also developed standards for the underlying air–ground subnetworks: in the VHF and HF bands, and also through satellite. More specifically, several technical choices or protocol stacks were proposed in the VHF band and are called VDL (VHF data link) mode 2 to 4.

Thus, considering aeronautical data link communications, in each successive generation, we found a set of application services (FANS), which uses an upper layers architecture (ACARS or ATN) based on lower layers architectures and radio systems (HF, VHF, SATCOM, etc.).

1.2.3.2. *VDL2 and ACARS over AVLC*

The first projects of implementation of ATN air–ground data link applications for air traffic services (both in Europe and the United States) considered continental dense airspaces. As stated before, performances of the air–ground subnetwork will comply with the operational environment, and the VDL mode 2 was selected as air–ground subnetwork for its high bandwidth, low delays capability and lower costs. It has to be noted that VDL mode 2 provides significantly more bandwidth than the equivalent subnetwork for ACARS.

For several reasons related to aircraft system’s architecture and operation, ACARS and ATN cannot operate on separate air–ground subnetworks, which would have required costly modifications. As a result, a transitory solution had to be found to allow ATSC applications using ATN to be hosted onboard aircraft with AOC and AAC applications using the ACARS network. Airline communications could have been carried on ATN as mentioned before, but this solution had not been selected. Indeed, compared to ACARS, ATN does not specifically address airline needs or services. Considering the costs that are required when equipping a fleet of aircraft and the ground end systems, there is real-added value, from an airline perspective, to switch to ATN only for AOC and AAC purposes. That is probably the main reason why ATN did not succeeded in replacing ACARS for these kinds of applications.

Several proposals were made (see [EUR 98]): carrying ACARS traffic on top of the transport layer, on top of CLNP or on top of ISO 8208. The industry consensus, however, led to use as few of the VDL mode 2 protocol stack as possible: only the protocols of the two first layers will be in common (i.e. physical and link layers).

This new ACARS subnetwork is called AOA (ACARS over AVLC), as the link layer protocol of the VDL mode 2 is called Aeronautical VHF Link Control (AVLC), and consists of tunneling ACARS blocks over an AVLC link. The old VHF subnetwork will be renamed POA to designate the old style VHF 2,400 bps transmission. Although these two acronyms contain the word "ACARS", they only deal with the air–ground VHF subnetwork part and do not modify the ACARS as a network system in any way.

With this new cost-effective subnetwork, DSPs may propose higher bandwidth to their ACARS customers, even in continental areas where no ATN-based air traffic service data link applications are planned on being deployed. In a way, ACARS customers will push for the deployment of a technology initially aimed to support ATN.

In the long term, however, it may not be desirable to keep both AOA and ATN VDL mode 2, as no prioritization mechanism is implemented across these two networks. The requirement to grant priority to safety-related communications cannot be met, and the threat of having more bandwidth demanding airline applications impairing delays may become problematic for ATSC.

1.2.3.3. *ATN and IP suite*

The ATN network was initially defined using ISO protocols compliant with the OSI model. Several SNDCFs were defined, one of which allowing OSI ATN to operate on top of an Internet protocol (IP) network.

In the current context of IP-based networks' supremacy and the obsolescence of X.25 networks, the legitimacy of an OSI-based ATN has been questioned, and an IPv6-based ATN architecture was developed. This architecture remaps the ATN ISO protocols into their equivalent in the IP suite: IP in place of CLNP, Transport Control Protocol (TCP) in place of COTP, BGP4 in place of IDRP, etc. The specification of the Aeronautical Telecommunication Network/Internet Protocol Suite (ATN/IPS) is described in [ICA 11], although this document is still in its draft version and has not been officially edited by the ICAO.

According to main actors, as long-term solution, next-generation ATN should operate over broadband IP instead of OSI protocols.

An IP-based ATN may lower acquisition and maintenance costs for the ground end systems and routers, as it is a Commercial Off-The Shelf-(COTS)based approach. However, when considering onboard avionics certification and retrofit costs, IP-based ATN system will probably not replace the currently deployed OSI ATN systems immediately, taking into account aircraft's lifecycle: airlines may be reluctant to retrofit aircraft already equipped with OSI ATN systems, and both ATN/OSI and ATN/IPS will coexist.

1.2.3.4. *ATN applications*

As stated previously, the applications defined within the ATN documents are very similar to those defined in FANS 1/A. However, they are not interoperable: one FANS 1/A aircraft cannot inter-operate with a ground ATN baseline 1 system and vice versa. In particular, for safety reasons, CPDLC adds a digital signature to the message, which is called the protected mode, hence it is called PM-CPDLC. Also, CPDLC message sets are not identical, and the ATN applications also provide an applicative acknowledgment of received messages known as Logical ACK (LACK) that does not exist in FNAS 1/A.

From an operational point of view, it is, however, possible to provide a certain level of accommodation between the FANS 1/A CPDLC and ATN CPDLC, so that differences are masked, avoiding displaying unnecessary information to the controller. In this case, the ground system will have to handle both protocol stacks.

ATN also defines the Context Management (CM) application which is equivalent to the AFN application in FANS 1/A: it is responsible for logging on to the ATC system, exchanging application addresses and versions along with flight plan data, so that the ground system is able to correlate a given flight plan and radar plot, with a set of application addresses. For a more detailed description of operational usage of and guidance material on data link for ATSC, refer to [ICA 13b].

The first implementation of ATSC data link using ATN in Europe defines a set of operational scenarios based on a subset of ATN services and applications. This definition is known as ATN baseline 1.

The corresponding avionics product is known as FANS 2/B+ (which is fully compliant with data link services mandate in Europe) and contains an ATN router and the ATN CPDLC and CMA applications. There is no ADS-C application here, as the intended airspaces are dense traffic continental areas with radar coverage, and ADS Broadcast is more suitable in this case. ADS Broadcast uses specific data link networks such as UAT and 1090 extended squitter with mandates starting in 2017 for Europe and 2020 for the US.

It is worth noting that integration of the FANS 2/B function with other avionic systems has been limited compared to FANS 1/A: few data are exchanged with the FMS, and clearances usually have to be entered manually. However, the radio frequency clearances may be loaded into the radio management interface: given the structure of the European airspace, a significant reduction in pilot workload and human errors are expected with this feature. Furthermore, voice will remain the primary means of communication in dense areas where FANS 2/B is deployed.

In spite of the numbering scheme used for these two products, which may be understood as a new generation of the same system, FANS 1/A and FANS 2/B have currently not the same operational scenarios, and the latter is not aimed at replacing the former in the current versions of the products.

However, work is underway on an ATN baseline 2 aimed at achieving convergence of oceanic and continental data link applications. Compared to ATN baseline 1, it aims to include oceanic operation and FMS integration into the current definition of the applications, in addition to providing new ATSC services. This new version should replace both FANS 1/A and FANS 2/B in the long-term, and is sometimes designated as FANS 3/C.

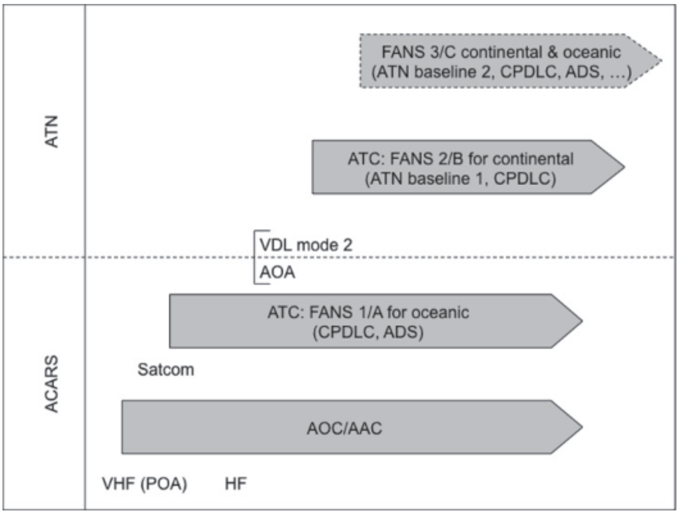

Figure 1.5. *Aeronautical communications steps*

1.2.3.5. *Deployment status*

Deployment of FANS 1/A was actively supported by the airlines as it allowed, in addition to safety enhancements, for significant fuel consumption reductions (User Preferred Routes and Dynamic Airborne Reroute Procedures).

Several ANSPs provide FANS 1/A type of ATSC all over the world (Atlantic, Pacific and Indian oceans, polar zones, Australia and Asia), and new deployments are planned in the coming years. Mandates for FANS 1/A equipage began in 2013 for the North Atlantic Tracks.

As shown in [SIT 13], D-ATIS, DCL/PDC and OCL are provided in several major airports all over the world. Some control centers also provide D-VOLMET.

Concerning ATN and FANS 2/B, the service is currently only provided in Europe. FAA CPDL Build 1A program planned to deploy ATNbaseline 1 with Miami as a first platform until the program was frozen in 2001. The Maastricht Upper Area Control Center operates data link applications since 2004. Aircraft equipage was on voluntary basis.

In 2009, the European Commission issued the regulation 29/2009 Data Link Services Implementing Rule (DLS IR), mandating for aircraft equipage of ATN baseline 1 CPDLC applications and the provision of these services in the European airspaces. An aircraft forward fit mandate began in 2011, and all the aircraft will be retrofitted in 2015. The service is currently deployed all over the European core area.

Table 1.1 summarizes the different air–ground communication means and traffic classes.

Area	Oceanic and remote		High-density continental	
Type	ATC	AOC	ATC	AOC
Voice vs. data	Data are primary means, voice is back-up (if equipped)	N/A	Voice is primary means, data are supplementary	N/A
ATC apps.	FANS 1/A: AFN, CPDLC, ADS	N/A	FANS 2/B: CM, PM-CPDLC	N/A
Network	ACARS	ACARS	ATN	ACARS
Subnetwork	POA, AOA, SATCOM	POA, AOA, SATCOM, HFDL	VDL mode 2	POA, AOA, SATCOM, HFDL

Table 1.1. *Air–ground communications means and traffic classes*

1.3. Radio subnetworks for air–ground communications

1.3.1. *Radio resource management*

1.3.1.1. *Frequency bands for aeronautics*

As any wireless communication network, ATN is subjected to the International Telecommunications Union (ITU, a specialized agency of the UNs) regulations for frequency allocation. In the following sections, the useful bands for aeronautics will be named according to the IEEE classification, as recalled in Table 1.2.

Frequency band	Frequency range	Wavelength
HF (high frequency)	3–30 MHz	100–10 m
VHF (very high frequency)	30–300 MHz	10–1 m
UHF (ultra high frequency)	300 MHz to 3 GHz	10 cm to 1m
L (long wave)	1–2 GHz	
Ku (Kurz-under)	12–18 GHz	
K (Kurz)	18 to 27 GHz	
Ka (Kurz-above)	27 to 40 GHz	

Table 1.2. *Frequency bands*

The allocation of frequencies was conducted over time to allow the coexistence of all services. The stakes are nonetheless very important; the available bandwidth is often the main limitation to the capacity of radio communication systems. Several HF sub-bands are allocated to civil aviation in between 2,850 and 24,890 kHz. The VHF civil aviation band extends from 108 to 136 MHz. Communication channels are defined over the 118–136 MHz range with 720 channels. New services will share the Distance Measuring Equipment (DME) L-band allocation. SATCOMs usually use frequencies L-band for the mobile service, with a planned move to Ka-band in the near future.

1.3.1.2. *Frequency sharing and multiple access*

Services are built on the basis of the frequency allocation. The main design step is to define the way this resource will be shared by the terminals. It is necessary to distinguish two concepts:

– the radio resource management. The objective is to define the smallest amount of radio capacity that can be attributed to one terminal. For example, the system can be designed using Single Channel Per Carrier (SCPC). In this case, terminals are attributed one carrier, i.e. one frequency sub-band, for the duration of the communication;

– the access method. The access method determines how the terminal will get and use the radio resource. The most basic method, as well as the least effective is to assign this resource statically. Deterministic techniques use a signaling mechanism to allocate the necessary resources to terminals for data exchange. Random techniques rely on mechanisms of competition between terminals with possibly capture effects.

Conventional techniques for managing radio resource allocation use two axes, frequency and time:

– frequency division. The principle consists of an existing subdivision into several sub-bands or channels. The allocation for each channel is conditioned both by regulatory constraints and the link budget. This mode is called Frequency Division Multiple Access (FDMA). Advanced transmission techniques use multiple channels simultaneously; we will introduce in particular Orthogonal Frequency Division Multiple (OFDM) for the L-DACS system in section 2.2.2.2;

– time division. The radio resource is shared between terminals on the basis of time intervals or bursts. This mode is called Time Division Multiple Access (TDMA). A resource actually available for a terminal corresponds to the allocated fraction of time;

– combination of frequency and time division. Many systems operate on two axes simultaneously. The radio resource is divided into channels, and a temporal structure is then defined. This mode is called Multi-Frequency Time Division Multiple Access (MF-TDMA). A well-known example is Global System for Mobile Communications (GSM) where 200 kHz channels are defined in which eight voice calls are then multiplexed using time intervals of 0.577 ms.

FDMA and TDMA methods use orthogonal resources: the transmission of multiple signals on the same channel and same time interval results in an interference level such that these signals cannot be demodulated and decoded (usually a received power difference allows a receiver to receive the strongest signal, the lowest signal can then be treated as an additional noise). The Code Division Multiple Access (CDMA) technique instead ensures the transmission of several signals in the same frequency band through special signal processing. Third-generation radiotelephony (3G or Universal Mobile Telecommunications System (UMTS)) is an example of using Direct Sequence Code Division Multiple Access (DS-CDMA). Each signal is composed of the encoded data stream "multiplied" by a spreading code specific to each terminal. The spreading code then acts as an encryption key. Only the receiver having knowledge of the spreading code can reconstruct the signal. Other signals act as an additional noise, and in this case additive. The SATCOM system ANTARES presented in section 2.2.2.3.3 is an opportunity to introduce a CDMA system.

1.3.1.3. *Random access basics*

As indicated in the preceding section, the access techniques fall into two main categories: deterministic or random access. Somewhat intuitively, it can be anticipated that random access presents a lower performance than deterministic access. Indeed, lack of coordination and competition between terminals would only lead to data loss. However, random accesses are fundamental to telecommunications networks. One reason is the random nature of many events in the network: terminal entry after power-on, establishing a new connection, arrival of a data stream, etc. A second reason arises from the complexity introduced by the signaling needed for radio resource allocation and the time required for this allocation. It may be preferable in some cases to accept a lower efficiency for the benefit of reduced complexity and a faster access time.

A first random access family is named ALOHA ("hello" in Hawaiian language, the University of Hawaii has been at the origin of the first publication on the subject [ABR 70]). The principle is as simple as possible: terminals share a single radio carrier and emit when they have pending data. The only constraint is the use of fixed size packets. The simultaneous transmission of two packets, even with a partial overlap, leads to a collision and a loss of both packets. In this case, the terminals are trying a new transmission after waiting a period of time determined by a probability law.

The ALOHA technique does not exceed 18% efficiency, which is extremely low. One way to improve the performance is to establish a time base, and then add to the constraint of fixed size packets the need for transmission within time slots. Access is then called S-ALOHA for Slotted-ALOHA, and maximum efficiency is limited to 36%.

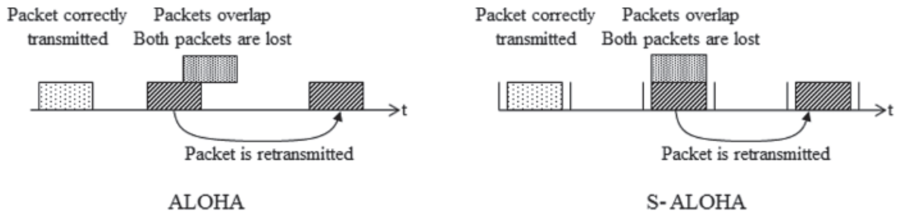

Figure 1.6. *Random access using ALOHA and S-ALOHA*

Figure 1.7 shows the performance of ALOHA and S-ALOHA using two parameters: the total load G and the efficiency S. G is calculated by summing the transmission time of all data packets and dividing by the observation time. For example, in case of S-ALOHA, G = 1 means that on average, a packet is transmitted in each time slot. Some slots have several packets that collide, other slots are empty. S is calculated by summing the transmission time of the correctly transmitted packets, i.e. without collision, and dividing by the observation time. Still in the case of S-ALOHA, S = 0.1 means that 10% of the time slots are used to transmit a useful data packet.

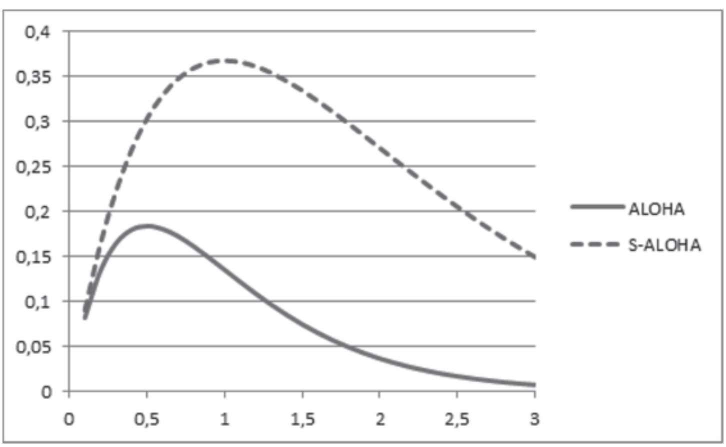

Figure 1.7. *ALOHA and S-ALOHA performances*

The previous trace provides several lessons. In addition to the highest available performance, it helps us to understand that random access techniques present a risk of instability. In the part of the curve with a positive slope, the access technique has a correct behavior: a network load increase (growing G) results in increased efficiency. Instead, the negative slope portion indicates that past a certain value of G (0.5 for ALOHA, 1 for S-ALOHA), the access method is unstable, since the growth of traffic in input results in a loss of efficiency. It should also be kept in mind that the gain in efficiency provided by S-ALOHA has a significant cost, as all terminals must be synchronized and propagation delays must be compensated or accommodated using guard times and timing advances. Implementing a time scale in a distributed system is always tricky, and it should be noted that most Local Area Networks (LANs) technologies do not use time division.

Several methods have been conceived in order to obtain a better efficiency and to increase the stability domain. In the case of networks where the propagation time is short compared to the transmission time of data packets, a first method both simple and effective is Carrier Sense Multiple Access: CSMA. This method is a common sense discipline. Before transmitting, a terminal listens to the activity on the channel and transmits only if the channel is free. CSMA thus implements a method to capture the radio channel: as soon as a terminal has been heard by all others in the service area, its data cannot encounter collisions. Adding additional discipline to the transmission still improves the behavior of the access method. Let us mention Collision Detect (CSMA-CD) for the first versions of Ethernet, Collision Avoidance (CSMA-CA) for Wi-Fi , etc. In the context which we are interested in, VHF data link VDL mode 2 illustrates CSMA p-persistent.

1.3.2. *VHF communications*

1.3.2.1. *ACARS*

The ACARS air–ground VHF subnetwork provides a data rate of 2,400 bps (to be shared among the aircraft) and uses a CSMA media access control algorithm.

The channels used for this subnetwork are allocated per region and per service provider in the ATC voice band (118–137 MHz). Each service provider has an exclusive allocation of one or more channels.

Transmissions are organized in fixed formatted blocks of 258 bytes. Each block may contain up to 220 bytes of user data among which the first bytes may be reserved for some header extension fields (message number and flight identifier). However, this block length limit constraint has been relaxed with the introduction of AOA. Moreover, blocks may be grouped to form messages.

Concerning error detection, each character in the block contains a parity bit (with the exception of a few fields in the block), and a 16 bit-long block check sequence code is added at the end.

Blocks will be acknowledged, but the ordering of the blocks is not guaranteed (connectionless protocol). Acknowledgments are sent piggybacked along with data or in a dedicated empty block. The size of the transmit window is limited to one: an ACARS router will wait for the acknowledgement of the previous block before sending the next.

Each block contains an identifier of the type of message called label that more or less identifies the sending application. Some labels identify ACARS subnetwork management blocks exchanged between the airborne router and ground ACARS system (e.g. link test and media advisory).

The address contained in the ACARS block always identifies the aircraft. Some variants introduce a way to address ground stations but usually, blocks are sent in broadcast mode. For downlink messages, the ground end system destination address is computed using the label, combined with the airline that registered the sending aircraft (i.e. it is not provided by the transmitting station).

Concerning ATSC, additional features are implemented on top of the above described protocol, which requires additional information to be added in each block. In particular, an additional ground address field is added as an extension field at the beginning of the user data field.

For bit-oriented applications, such as CPDLC and ADS-C, a bit-to-character conversion is applied. It has to be noted that this conversion divides the throughput by a factor of 2: binary data are simply written in the character representation of the hexadecimal value of each byte.

1.3.2.2. *VDL mode 2*

As described in [ICA 01], VDL mode 2 has been developed as a mobile subnetwork supporting ATN, thus complies with ATN requirements: it provides the required interfaces by implementing the ISO8208 protocol. This network protocol allows establishing Switched Virtual Circuits (SVCs) between the airborne ATN router and one or more air–ground ATN routers through the VDL mode 2 air–ground subnetwork, thus providing multiplexing and segmentation/reassembly on top of the link layer connection. Here, both air–ground and airborne ATN routers are seen as Data Terminal Equipment (DTE) while the ground VDL mode 2 subnetwork interface is seen as a Data Circuit-terminating Equipment (DCE). The required ground DTE addresses are exchanged through the link layer in specific identification frames, as described below.

At the link layer, the VDL mode 2 implements a slightly modified High-Level Data Link Control (HDLC) protocol, named AVLC. The main differences with HDLC have been brought with the intent to handle the mobility of the airborne stations and to reduce unnecessary transmissions.

Airborne stations' mobility features concern ground station identification, link establishment and handover procedures, and have been designed so as to allow sharing a single frequency among several service providers.

These procedures are handled by two dedicated management entities, and use tailored XID frames. These frames convey all the parameters to be used or negotiated, along with necessary ATN router connectivity information and frequency management.

AVLC defaults to transmit up to 1,024 bytes long frames with a transmit window size of four frames. Retransmission timer values adapt to the channel utilization and the number of preceding retransmissions. Acknowledgements are sent with a small delay to increase the probability of having the acknowledgement piggybacked with upper layers data. Finally, AVLC uses selective reject to request the retransmission of lost frames (as opposed to the go-back-n way of working) with the ability to acknowledge multiple well-received frames.

The AVLC also provides a connectionless service that may be used for broadcast services which is currently not in use. Frames are sent through p-persistent CSMA, which will be described in the next section.

Finally, on the physical layer, bursts are seen as containers that may convey several AVLC frames in a single media access. Bursts contain Forward Error Correction (FEC) codes (up to 6 bytes in a block of 255) combined with interleaving technique to improve the transmission efficiency.

At the physical layer, VDL mode 2 provides a throughput of 31,500 bps and uses VHF 25 kHz channels in the 118–137 MHz band. VHF air–ground data link communication channels are allocated in the range 136.900–136.975 MHz as required in [ICA 13.a]. A worldwide Common Signaling Channel (CSC) for VDL mode 2 has been allocated on the 136.975 MHz channel, and channels have been allocated for VDL mode 2 in Europe. The network architecture for VDL mode 2 is summarized in Figure 1.8.

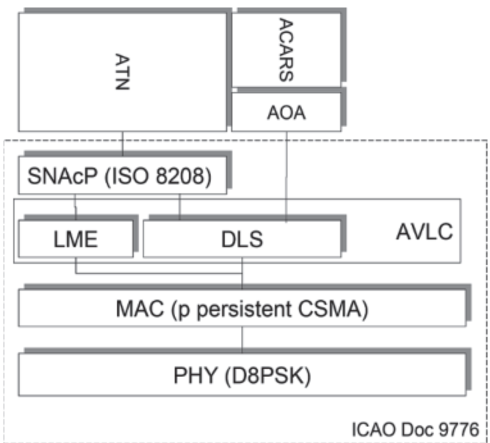

Figure 1.8. *VDL mode 2 protocol stack*

Mobility management in VDL mode 2 is based on several structural, technical or operational constraints. First, we can note that the aircraft system is the only to know when it needs to establish the communication with the ground. Second, an aircraft sends data to a very limited number of ground stations (usually 1, sometimes 2), while the ground station will have to send data to several tens of aircraft. The aircraft is thus able to build a view on the quality of the transmission with the surrounding ground stations without requiring additional transmissions, which is not true for the ground station. Finally, VDL mode 2 will allow sharing the same frequency for several DSPs, which suppose that all the ground stations operating on a given frequency will not be considered equally. Moreover, for scalability reasons, it is reasonable to be able to define groups of ground stations in large continental areas instead of having a suboptimal single global VDL 2 subnetwork. This concept is known as a VDL mode 2 ground system, where procedures between ground stations belonging to the same ground system are not applicable if they do not.

Mobility management is undertaken by the VDL Management Entity (VME). It is the VDL mode 2 system wide entity responsible for the management of and interaction with the peer systems: there will be one VME per system, regardless of the number of ground stations. It creates a Link Management Entity (LME) for each peer system with which a link connection is to be created. An LME lasts as long as a link is alive with the corresponding peer system, so LMEs manage one or several Data Link Entities DLEs which handle the link layer connection (data sending and receiving) as shown in Figure 1.9.

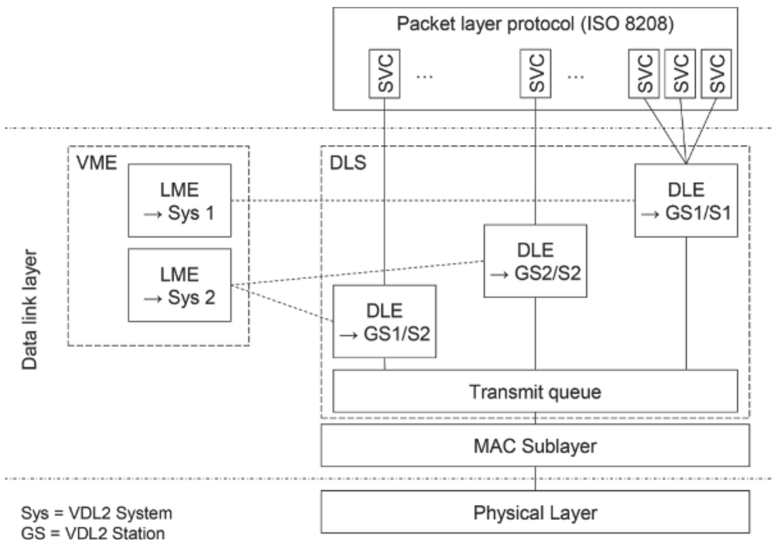

Figure 1.9. *Data link layer overview*

The first step in the mobility management of VDL mode 2 is, obviously, the detection of the service by the avionics systems. This requires monitoring the transmissions on the frequencies known (or assumed) to be operated by VDL mode 2 service providers (which may be commercial DSP or an ANSP). The CSC acts here as the worldwide default frequency and is the first frequency an airborne system should listen to when it starts up. By doing this, airborne systems are able to determine all the ground stations in the aircraft radio coverage and analyze the signal quality. Several signal quality analysis processes are listed in the technical manual. Received signal strength is the recommended and commonly implemented one.

However, all the required information concerning the ground stations and available services (e.g. connectivity to ground ATN routers) will be transmitted by the ground stations. They are sent in a dedicated frame called the Ground station information frame (GSIF). These frames are sent on a regular basis and provide the link layers parameters to use with the considered ground station and, in addition, any useful information for the avionics systems: mask to determine the different ground systems, alternate frequencies, destination airport, ATN routers for ATC or AOC. Thus, GSIF frames have the twofold aim of providing the required information to interoperate with the ground station and to maintain the minimum activity of the ground station so that aircraft can detect VDL mode 2 activity.

The choice to log on a given VDL mode 2 ground system and to connect to one of its ground stations is then driven by the services requested by the avionics and the ones offered by the ground system, which are determined through the parameters and data provided in the GSIF. It will mainly be driven by airline commercial policy (e.g. preferred DSP) and offered services (e.g. ATC/AOC ATN routers, AOA, etc.). Hence, this decision is outside the scope of the VDL mode 2 subnetwork itself: within the ATN description, it is delegated to the Intermediate System – System Management Entity (IS-SME). Of course, today implementations may vary from this description, especially since the introduction of AOA, which supports AOC applications communications outside the scope of the ATN network.

Once the decision has been made, the airborne initiate the link establishment by sending an XID_CMD_LE, and the ground stations accept by sending an XID_RSP_LE as shown in Figure 1.9. The aim of this procedure is two-fold: establish the link layer connection and act as a log-on procedure from the airborne system into the VDL mode 2 ground system. Once accepted, the ground will create the corresponding LME to handle the links with the airborne system which will be established through different ground stations along the flight.

At this point, data may be exchanged between the airborne system and ground station: non-8208 service (e.g. ACARS blocks) may be sent on top of the link layer connection, after having tagged the transmission in compliance with ISO/IEC TR 9577 so as to differentiate with the ATN services. There is one specified to designate AOA service. However, additional exchanges are required for the ATN protocol stack to build a viable communication path: ATN routers will be interconnected, and routing information is required to be exchanged.

The airborne router will establish virtual circuits with at least one air–ground router as provided in the GSIF. At the same time, the two routers have to declare themselves to each other and exchange some configuration information. This step is required so that the routing protocol IDRP is able to create an adjacency and have the minimum routing information to send IDRP packets to the other router (through CLNP). This step is performed through the sending of the Intermediate System Hell (ISH) PDU of the End System – Intermediate System (ESIS) routing protocol as described in the "Report configuration" function of ISO 9542.

The airborne station will continuously monitor the quality of the current transmissions and also of any other stations (regardless of ground system boundary) and store information on other operated frequencies. Indeed, the airborne system may have to handover to a new ground station for several reasons: poor quality of the current ground station transmissions (e.g. signal strength) compared to others, maximum retransmission count exceeded on the current data link connection, congested frequency channel or silent ground station. In any of these cases, a new ground station will be chosen, with the same provided services as far as possible. If the selected ground station does not belong to the same ground system, the airborne system will have to use the link establishment procedure presented here above, as it has also to log on the new ground system, and the old link will be explicitly disconnected by sending a DISC frame.

There are several different variants for handing over a connection from one ground station to another within the same VDL mode 2 system. We will only describe the two that are currently implemented: air-initiated handoff and ground requested air-initiated handoff.

VDL mode 2 implements a "make-before-break" way of handing over a link layer connection from one ground station to the next one within a single ground system. As shown in Figure 1.10, the two LMEs will establish a new link by exchanging XID_CMD_HO (sent by the aircraft) and XID_RSP_HO frames. Note that for these frames, the HDLC Poll/Final bit will be set to 1. On acceptance of the handover, a timer (TG5) will be activated on both sides to silently disconnect the old link after a few seconds. This delay will allow reestablishing the subnetwork connections if necessary (ATN only). As a subnetwork layer virtual circuit is only valid on the underlying link layer connection on which it has been established, each of the established circuits will be reestablished when a handoff is performed.

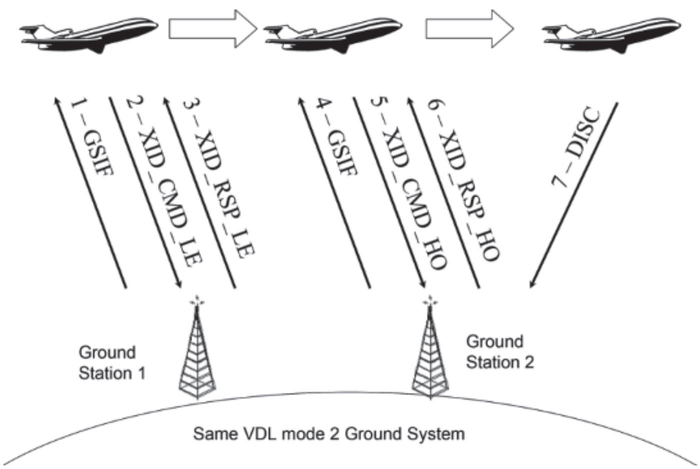

Figure 1.10. *Link establishment, handover and disconnect procedures*

The ground system may also be willing the aircraft to perform a handoff, primarily (if not exclusively) for channel load management. For this kind of situation, a VDL mode 2 ground system may request the avionics system to initiate a handoff, and optionally to tune to another frequency at the same time. On reception of a handover request, the avionics system will perform the handoff, just like described here above. Obviously, in the case the radio has been retuned, it is not possible to properly implement a make-before-break handoff with only one radio: communication on the previous frequency becomes unavailable as soon as the radio has been retuned to the new one.

VDL mode 2 implements p-persistent CSMA. Before starting a transmission, a station will sense the channel. If the channel is busy, it will persist in sensing the channel until the latter becomes idle. When the channel is or becomes idle, the station determines whether it will transmit through a random process, the outcome of which being that the station will transmit with a probability of p and wait for an additional delay of TM1 with probability (1-p). After TM1, the station will restart the above described process, except if there was already M2 attempts, in which case it will transmit (no random process). In addition, the complete process will not take more than TM2 seconds, or the channel will be declared congested and the transmission will be cancelled (obviously, the radio should not be tuned to another frequency). The default values for these parameters are given in Table 1.3.

Parameter	Default value
P	13/256
M1	135
TM1	4.5 ms
TM2	60 s

Table 1.3. *VDL mode default parameters*

P-persistent CSMA may be implemented as shown in Figure 1.11, except for the timer TM2 which is not described.

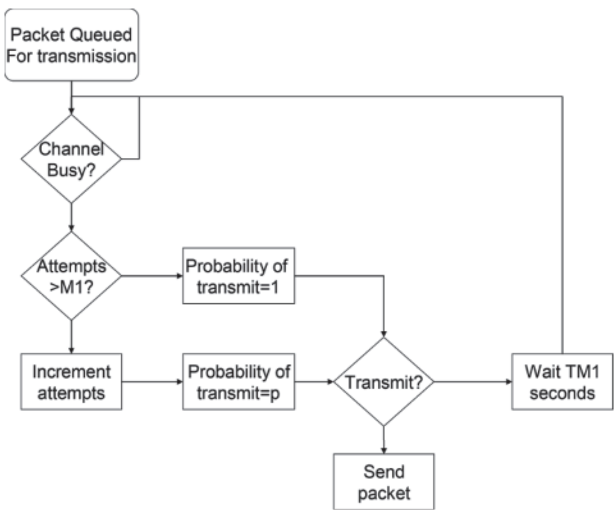

Figure 1.11. *p-persistent CSMA*

Several simulation studies have been conducted since the first definitions of the VDL mode 2 subnetwork. In particular, EUROCONTROL led several simulation campaigns, in the frame of the Link 2000+ project. These simulations aimed at providing planning data for the European VDL mode 2 deployment.

EUROCONTROL simulations are based on real aircraft traffic traces (peek day) and are representative of data link application message profiles. The first set of simulation aimed at determining the limit of the first VDL mode 2 channel (CSC) with regard to the round trip delay requirement on the subnetwork part: the apportionment of the most stringent application requires the round trip delay to be less than 8 s in 95% of the transactions. These simulations showed that a single VDL mode 2 channel should be able to support the migration of the ACARS traffic, plus the ATN CPDLC traffic required if a third of the aircraft were equipped. This means that a second channel will be operated by the DSP early enough before this threshold is reached so as to guarantee that the performances are compliant with the requirements provided in [EUR 04].

Other simulation campaigns were performed by EUROCONTROL with the intent to study p-value influence on performances and multichannel deployment scenarios. Simulations showed that some performance improvements may be achieved by fine tuning the value of the probability and in particular by using a higher value for ground stations than for aircraft.

Finally, the simulation tool was also used to evaluate the number of additional VDL 2 channels to be operated so as to cope with increasing Link 2000+ equipage ratios to support ATN CPDLC application in Europe. Results gave reasonable confidence in the need for two or three additional channels for the core area in Europe to keep peak traffic day round trip delay below 8 s.

EUROCONTROL also implemented tools with the intent to monitor interoperability and performances of the VDL mode 2 subnetwork in compliance with European regulation 29/2009 and [ICA 13b] requirements.

1.3.3. *SATCOM*

SATCOMS provide a reliable, high-quality link practically over all regions of the globe. In the context of ATC, two systems are available: the

Inmarsat geostationary satellites, currently generations 3 and 4, and the Iridium low Earth orbit satellites. Both systems are approved by the ICAO, the first since 1995, the second since 2012. Civil aviation uses mainly the Inmarsat services, with about 2,000 equipped aircraft. Business aviation also widely used Inmarsat; Iridium offers itself as an attractive alternative.

1.3.3.1. *Geostationary satellites and related constraints*

The vast majority of data traffic carried by satellites is handled by geostationary spacecraft. This is a consequence of the major characteristic of the geostationary orbit: as the satellite is placed on a trajectory in the equatorial plane with an altitude of 35,786 km, the revolution period is equal to a sidereal day, i.e. 23 h, 56 min and 4 s. The satellite is thus seen as a fixed point in the sky, and permanent communications can be provided. Three geostationary satellites provide complete Earth coverage, with the noticeable exception of the poles.

The advantages of a geostationary orbit from a geometry perspective are, however, accompanied by constraints in the design of the communication system. The long distance to be traveled by the radio signal rises a significant propagation time of about 125 ms between satellite and ground. The corresponding delay is 250 ms and is particularly noticeable during a telephone conversation. Furthermore, the attenuation undergone over this distance is of course much higher than that observed in terrestrial systems. Achievable data rates may nevertheless be very high in some cases. The public is familiar with the use of satellite dishes for direct television broadcasting. The combination of directional antennas, high-power amplifiers onboard the satellites and high frequencies (for example, Ku-band 10/12 GHz) leads to links of several hundred Mbit/s. In the case of aeronautical communications, however, the satellite links use the L-band (around 1.5 GHz) and low-directional antennas. Data rates are then amounting to tens of kbit/s.

1.3.3.2. *Definition of AMSS*

AMSS is the satellite communication service defined by the ICAO. Annex 10 describes the general architecture and communication protocols that are used in this context. The initial AMSS service was exclusively based on the Inmarsat system, and the first AMSS SARPs versions were more or less a translation of the Inmarsat System Definition Manual (SDM) for AMSS [ICA 06]. Since [ICA 07], SARPs have been written in a more agnostic manner, mainly addressing performance constraints and thus enabling the introduction of new systems. Within the Inmarsat service panel, AMSS is referred to as a “Classic Aero” satellite system. “Classic Aero” services are available across seven Inmarsat satellites (four I-3 and three I-4 satellites). One MTSAT satellite completes the float. All Inmarsat satellites operate a global beam that covers around one-third of the Earth surface excluding the poles. I-3 satellites are designed with five spot beams where the link budget is enhanced due to the additional satellite antenna gain (6 dB gain). Similarly, the I-4 satellites support 19 spot beams.

The AMSS system consists of three segments: the ground segment, space segment and aerospace segment. The ground segment comprises ground stations spread all over the world in order to ensure the interface between the ATN network and AMSS subnet. These Earth stations, called GES for Ground Earth Station, are managed either by Inmarsat (I-4 Hawaii and Fucino gateways) or by various telecom operators (I-3 gateways). The space segment consists of a number of satellites that provide a full coverage of the globe with the exception of the poles. In the context of AMSS, satellites are considered as transparent; therefore, they act as amplifiers of the microwave signals, but do not have a function of the network level. The Iridium system will be an opportunity to discuss the features of regenerative satellites. The aviation segment corresponds to stations implemented on aircraft. These stations, called AES for Aeronautical Earth Station, provide an interface between the satellite link and networks embedded in the plane. Figure 1.12 shows how the integration is performed satellite links in the ATN architecture. It should be noted the direct link between GHGs and AES, thus confirming the hypothesis of a transparent satellite.

Satellite links use frequency bands as defined by the ITU-R. The ITU regulations distinguish so-called fixed and mobile services. In the case of AMSS, the links between GES Earth stations and satellites are covered by the fixed service, and will therefore use either C-band, Ku or Ka links. Instead, the links between satellites and aircraft are of the mobile service type and use the L-band allocation for AMSS. The corresponding bands correspond to 1,525–1,559 MHz for the downlink (satellite to aircraft) and 1,636.5–1,660.5 MHz for the uplink (aircraft to satellite). Within these bands, two sub-bands have an exclusive allocation for critical communications: 1,544–1,555 MHz and 1,645.5–1,656.5 MHz. Communications for ATC/AOC fall in this category: distress calls and urgency communications, flight safety messages, meteorological and flight regularity messages.

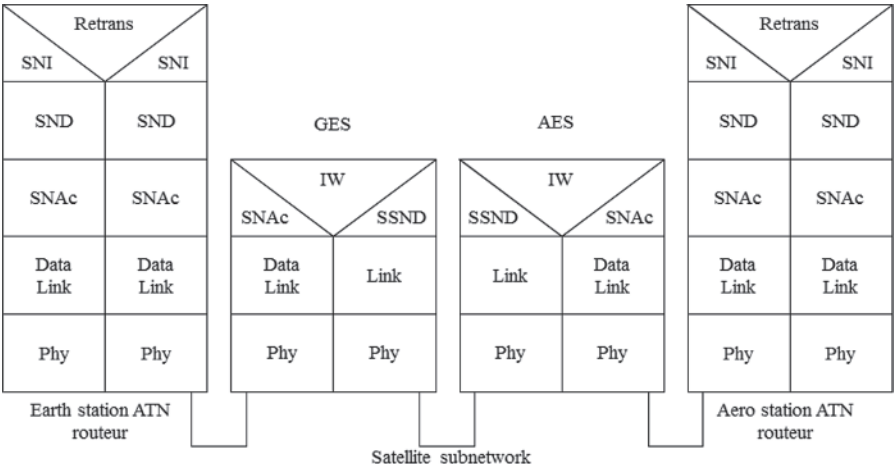

Figure 1.12. *AMSS subnetwork*

1.3.3.3. *Physical channels:*

Four physical channels are defined: P, R, T and C. The access technique is different for each channel. All channels cannot be handled by all AES. Four service levels are identified depending on available channel rate and accessible channels:

AES level	P channel	R channel	T channel	C channel
1	0.5 and 1.2 kbit/s	0.5 and 1.2 kbit/s	0.5 and 1.2 kbit/s	NA
2	0.5 and 10.5 kbit/s (4.8 kbit/s)	0.5 and 10.5 kbit/s (4.8 kbit/s)	0.5 and 10.5 kbit/s (4.8 kbit/s)	NA
3	0.5 and 10.5 kbit/s (4.8 kbit/s)	0.5 and 10.5 kbit/s (4.8 kbit/s)	0.5 and 10.5 kbit/s (4.8 kbit/s)	8.4 and 21.0 kbit/s (5.25, 6.0 and 10.5 kbit/s)
4	Same as 3 with simultaneous use of C and R/T channels			

Table 1.4. *AMSS service levels*

Service levels are related to the Inmarsat "Classic Aero" capabilities as presented in the Table 1.5 [ICA 10a]:

Service	Antenna type	Global beam operation	Spot beam operation	Data channel rates	Circuit switched channel rates
Aero-L	Low gain (nominally 0 dBic)	Y	N	600, 1,200	
Aero-I	Intermediate gain (nominally 6 dBic)	N	Y	600, 1,200	8,400
Aero-H	High gain (nominally 12 dBic)	Y	Y	600, 1,200, 10,500	21,000
Aero-H+	High gain (nominally 12 dBic)	Y	Y	600, 1,200, 10,500	8,400, 21,000

Table 1.5. *Inmarsat "Classic Aero" services*

The physical channels are defined by the direction and access technique:

– P channel. P stands for Packet. The P channel is dedicated to the communications from Earth stations (GES) to the aircraft (AES). GES transmits a continuous carrier and multiplexes data (Time Division Multiplex (TDM)). The P channel carries both signaling and data packets. Aircraft recover data by address filtering. The main benefits of the TDM access are its simplicity and capability to multiplex unicast (from GES to one single aircraft), multicast (from GES to a group of aircraft) and broadcast traffic (from GES to all aircraft).

– R channel. R stands for Random. The R channel is used from aircraft (AES) and ground station (GES). The access technique is slotted Aloha. Data are transmitted on the basis of packets in predefined time slots. The very simple S-ALOHA random access technique has the drawbacks of limited efficiency (maximum 36%) and potential instability. Its use is, however, compulsory to manage entry procedures and can still be well fitted to very short messages.

– T channel. T stands for TDMA. The T channel is also used from aircraft (AES) and ground station (GES) and complements the R channel. On the contrary to random access, time slots are here dedicated to a single aircraft at a time. This means that the ground station GES runs an allocation process and sends signaling to aircraft with a time burst time plan. Obviously, the management of time slot allocation is a costly process but this is the only way to allow the reliable and timely transmission of long messages.

– C channel. C stands for Circuit. Circuit-mode SCPC channel is used in both forward and return directions to carry digital voice or data/facsimile traffic. The use of the channel is controlled by assignment and release signaling at the start and end of each call or fax transmission.

AMSS uses phase modulation. Low data rates are accommodated using Binary Phase-Shift Keying (BPSK) (0.6, 1.2 and 2.4 kbit/s). Higher data rates are transmitted using Quadrature Phase Shift Keying (QPSK). The allocation for each carrier is defined with a 2.5 kHz step. As a result, the lowest rate data channel will occupy a bandwidth of 2.5 kHz; the highest data rate channel is 15 kHz. Radio transmission uses right-hand circular polarization.

On P, R and T channels, data are structured using fixed-size Signaling Units (SUs): 96 bits for P and T, 152 bits for R. Figure 1.13 shows the format for frames on P channel.

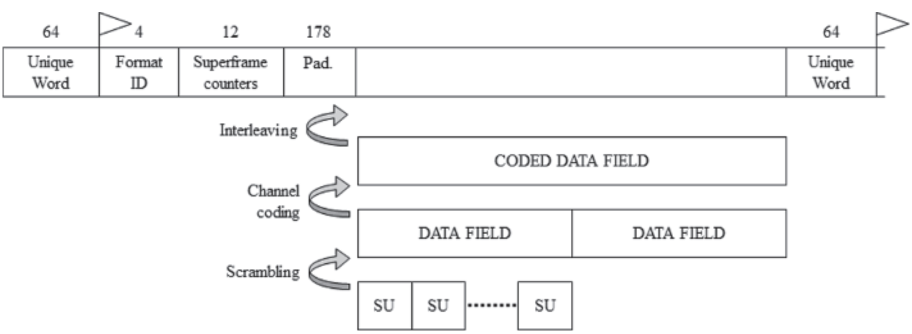

Figure 1.13. *P frame format (4.8 and 10.5 kbit/s)*

A unique word, i.e. a preset bit sequence, is introduced in order to delineate the frames. Then, frame format identifier and frame counters are defined. SUs are sent in sequence, the number of SUs per frame is set so that the frame duration equals 500 ms (rates higher than 1,200 bit/s). As an example, a 10.5 kbit/s frame can accommodate 26 SUs. Scrambling randomizes 0 and 1 distribution using a pseudo-random sequence. Channel coding is a simple yet robust ½ convolutional coding. Interleaving enhances the decoding process; errors occurring in bursts during transmission are "spread" over the frame with a close to uniform distribution. This process is conducted by writing successive coded bits in a table following lines. Coded bits are then sent to the modulator reading columns.

As the P frames are transmitted continuously by the Earth station GES, they provide a simple way to synchronize aircraft stations. Figure 1.14 shows the time relation between P channels and time slots for the R channel. It should be kept in mind, however, that these timescales are defined at the GES, so the timescale for R channels corresponds to reception. Aircraft must anticipate transmission and apply a timing advance. In the case of AMSS, data rates are low, and slots have a large aperture, so the knowledge of the aircraft position and nominal satellite position is precise enough to calculate this timing advance.

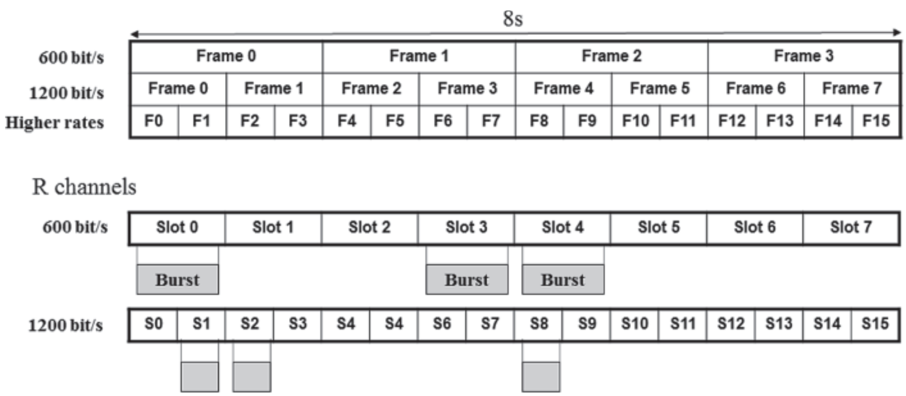

Figure 1.14. *Timing relation between P and R frames*

Figure 1.15 shows the format for R channel bursts. The preamble is a set of predefined symbols that enable the receiver synchronization. The unique word delineates the burst. The coded block encompasses an extended SU in order to fit in one interleaver block.

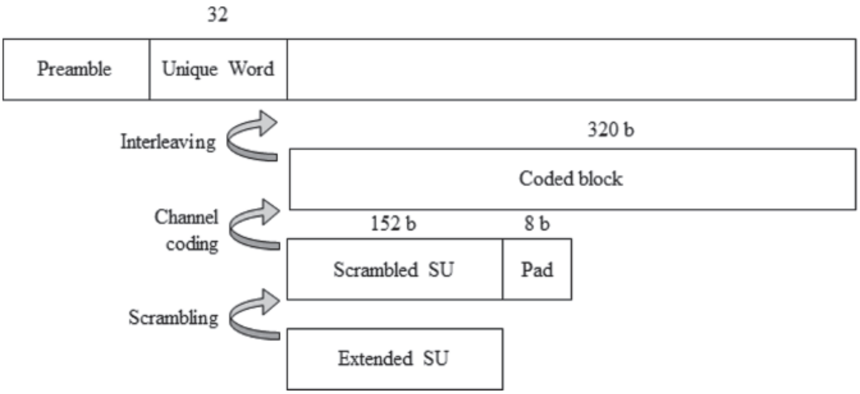

Figure 1.15. *R slot format*

Figure 1.16 shows the format for T channel bursts. T bursts are so defined that they can be sent over several time slots. That is why from 2 to 31 SUs can be accommodated in the burst.

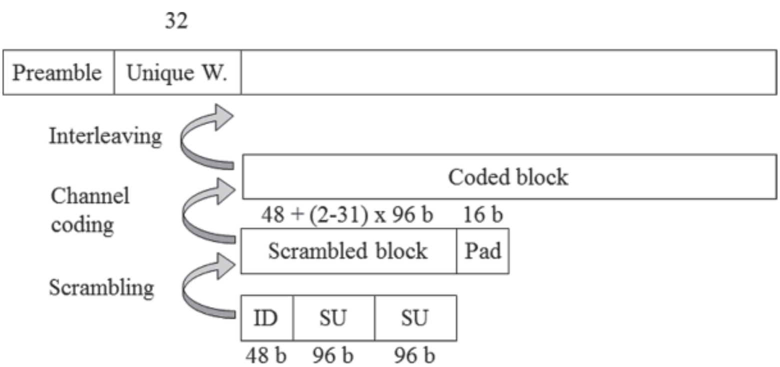

Figure 1.16. *T slot format*

SUs do not have a generic format. On the contrary, the standard describes all the SUs needed for signaling and data exchanges. This per-field format description allows optimizing the SUs size at the detriment of flexibility. Figure 1.17 presents a typical SU format, in this case a connection request from GES to AES on a P channel. GES Identifier is coded over 1 byte, AES Identifier over 3 bytes. A noticeable field is Q number used for priority management. Q = 15 denotes an emergency message, zero corresponds to the lower priority.

Message type	1B
AES ID	3B
GES ID	1B
Q	4b
Reference number	4b
Reserved	4B
CRC	2B

Figure 1.17. *SU format (connection request on P channel)*

1.3.3.4. *Procedures*

Numerous procedures are defined for communication management and data services. The objective here is not only to exhaustively describe them but also to give the main principles.

The first presented procedure is the AES network entry. After switching on, the AES terminal must first recover the parameters of the AMSS system. To do so, a set of Psmc 0.6 kbit/s carriers is explored. As soon as a Psmc carrier is detected, information broadcasted by the corresponding Earth station can be received.

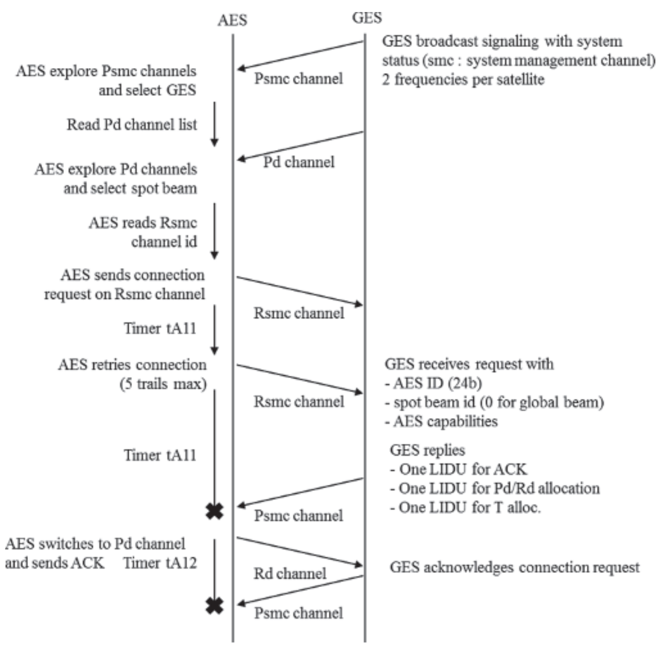

Figure 1.18. *AMSS entry procedure*

AMSS does not implement actual handover procedures as in mobile networks. However, it may be necessary for an AES to move from one satellite to another one (or from one regional beam to another one). One of the following events may trigger the handover procedure: P-channel degradation (detected either by loss of clock synchronization for more than 10 s or failure of log-on renewal), satellite below elevation handover threshold with another satellite being at least 1° higher than the log-on satellite for more than 10 s and user command. As a result, AES proceeds with log-off (except P-channel degradation) then connects to the new GES applying the procedure presented in Figure 1.18. This means that the continuity of connection and communication is not assured.

The next presented procedure is data transmission over the T channel. For short data messages, i.e. up to 33 bytes, transmission is achieved with random access on the Rd channel. A 33 bytes message will be segmented in three 11 bytes SUs, and thus uses 3 bursts. A selective acknowledgment triggers retransmission of lost parts (either because of uncorrected errors or collisions). For longer messages, AMSS relies on a reservation of time intervals on the T channel. Figure 1.19 shows the used sequence: a first burst on the Rd channel is sent in order to carry a reservation demand. If successfully received by the GES, a capacity allocation is transmitted on the Pd channel. As for all random access, a timer is set by the AES so that the capacity request can be retransmitted if no answer is received from GES. Data can then be transmitted in the allocated time interval on T channel. Piggybacking is used to transmit new capacity requests.

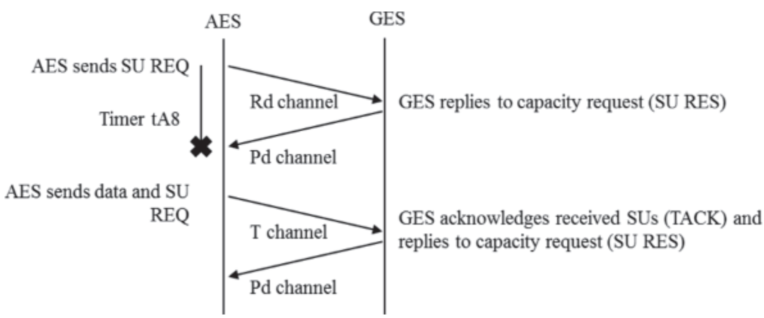

Figure 1.19. *Capacity requests and resource allocation*

1.3.3.5. *MTSAT AMSS capacity augmentation*

Multifunctional Transport SATellite system (MTSAT) satellites are operated by the Japan Meteorological Agency (JMA) with several dual missions: aeronautical communications, satellite-based augmentation systems and meteorological imagery. The MTSAT communication service is provided by the Japanese Civil Aviation Authority (JCAB) and is fully compliant with the AMSS standard. Interoperability tests and operational integration of the JCAB regional AMSS service within the Inmarsat global system have been conducted in 2006. It thus provides a capacity augmentation of the Inmarsat service over the Asia region. The satellite currently in operation is MTSAT-2.

1.3.3.6. *LEO satellites alternative, brief presentation of Iridium*

Iridium is a system of communication satellites in low Earth orbits. The satellites are placed at an altitude of 781 km. Sixty-six active satellites are needed to provide complete coverage of the Earth, 10 spare satellites are also deployed for system reliability [ICA 10a]. The system management is relatively complex, since the visibility period of each satellite is limited (about 10 min), which involves handover during communications. Handover is also needed between beams, as the satellite coverage is ensured by a 48 beam-phased array antenna. In addition, Iridium satellites are regenerative and form a mesh network in the sky. This network is based on intersatellite links (ISLs) in the 23.18–23.38 GHz band. Each satellite maintains four crosslinks to adjacent satellites. All communications are handled by the two gateways in Arizona and Hawaii due to Ka steerable feeder links.

Iridium services comprise voice communications with a data rate of 2.4 kbit/s and various data services: dial-up data with a throughput rate of up to 2.4 kbps, direct Internet data with a throughput rate of up to 10 kbps and short burst data (SBD) service. A new satellite constellation, Iridium Next, will take over existing satellites with greatly increased capacities. Throughputs greater than 1 Mbit/s are advertised for L-band terminals, 8 Mbit/s for Ka-band terminals. Service entry is planned in 2017.

1.3.4. *HF communications*

The HF band corresponds to wavelengths between 10 and 100 m and has a frequency range of 3–30 MHz. HF communications are a traditional way for voice that may also use channels in the Medium Frequency (MF) band (300 kHz–3 MHz). Voice is transmitted using a modified amplitude modulation called single-sideband modulation (SSB). Due to the migration of services to data, it became necessary to implement data links in the HF band (HFDL). HFDL installations are designed so that they can operate using any SSB carrier frequency available to the aeronautical mobile service in the band 2.8–22 MHz. A major motivation for HFDL besides the low cost is its complementarity in terms of coverage with Inmarsat satellite system: HFDL provides service to latitudes higher than 75° N and thus is available to aircraft on polar routes.

1.3.4.1. *Beyond line of sight communications using HF*

The main characteristic of HF transmissions is the ability to establish links beyond line of sight. Two physical phenomena are used for this purpose. The first phenomenon is ground waves for frequencies less than 1.6 MHz; this phenomenon is not used by the HFDL data link that operates at higher frequencies. The second phenomenon is based on the properties of the ionosphere layer of the atmosphere between 60 and 800 km where a partial ionization of gases is observed. Refraction of electromagnetic waves in the HF range within the ionosphere allows propagation over long distances.

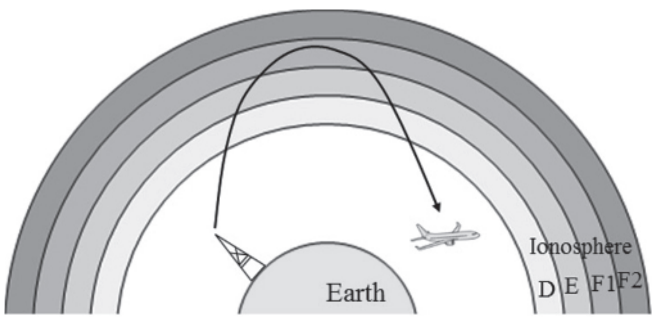

Figure 1.20. *HF propagation through the ionosphere*

Propagation conditions are, however, mainly conditioned by the solar activity, including sunspot cycle peaks, and several atmospheric layers are involved: D (60–90 km), E (90–150 km), F1 (150–250 km) and F2 (250–400 km). Typically, D and E layers disappear and F1 and F2 combine into one at night. This means that all channels are not available for transmission all the time, what is more the day/night frontier can block the link. However, HF is used almost since the beginning of commercial aviation, the knowledge of the propagation phenomena is very accurate, and a prediction of operable frequency bands is available.

At present time, HFDL is operated by 17 ground stations spread all over the world. Each ground station operates a subset of the available HFDL channels.

1.3.4.2. *Implementation of data link using HF channels, motivation, access method and expected performances*

The HFDL data link, unlike voice connections, uses phase modulation of BPSK, QPSK and 8PSK types. These modulations have a symmetrical spectrum around the center frequency, which is not the case of SSB modulation. Figure 1.21 shows the definition channels for HFDL. It should be noted that the reference frequency of the channel (the one found in the regulatory documents) is shifted to 1.4 kHz from the center frequency of the phase modulated carrier. The channel spans over 3 kHz.

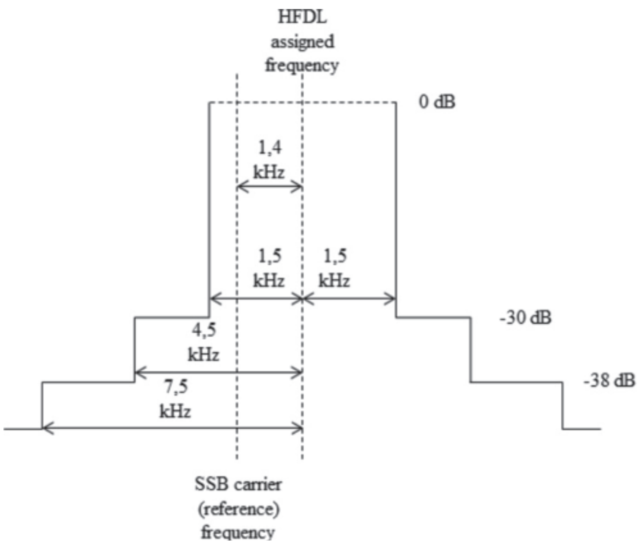

Figure 1.21. *HFDL channel definition*

The symbol rate is set to 1,800 symbols per second. Forward error correction is applied to data, and four data rates are available: 1,800 bit/s (8PSK), 1,200 bit/s (QPSK), 600 and 300 bit/s (BPSK). The opportunity to change modulation and coding allows for data rate adaptation: depending on the received signal-to-noise ratio, the waveform can be adapted in order to obtain the best spectral efficiency. Considering one carrier, the access method is a duplex time multiplex (TDMA). Frames are defined on a 32 s basis, each frame encompasses 13 time slots. Slots can be used either for uplink or downlink.

The first time slot in each frame is transmitted by the ground station. This slot called "squitter" delineates the frame and broadcasts signaling information: system status, timing reference and protocol control. Each ground station has a time offset for its squitters, so that aircraft can jump between ground stations and find the best one before logging on. Remaining slots can be either uplink slots (from ground station to aircraft), downlink reserved slots (from aircraft to ground station) or downlink random access slots. Random slots are needed for log-on and capacity requests; the access method is then S-ALOHA. Reserved downlink slots ensure that data will be transmitted without collision.

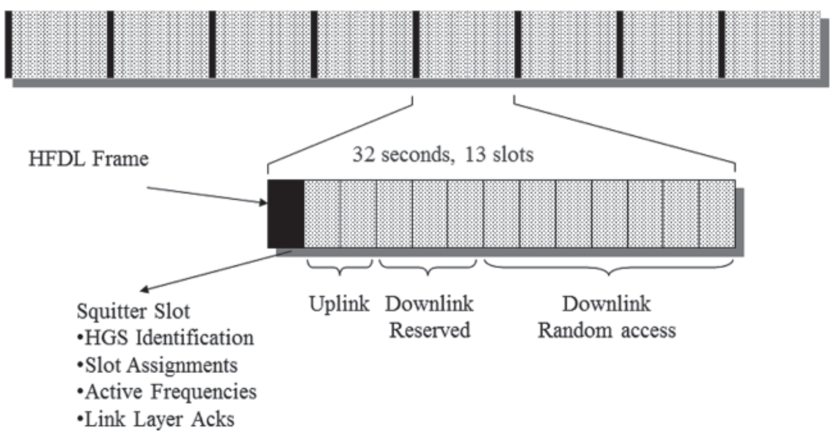

Figure 1.22. *HFDL frame typical configuration*

1.3.4.3. *Performances*

Obviously, the long frame format prevents HFDL from providing short transfer delays. Large time slot aperture is imposed by the low data rate and long range. However, maximum transfer delay (95 percentile) from ground station to aircraft is expected to be less than 90 s for high priority messages (11 through 14) and 120 s for low priority messages (7 through 10). In the opposite direction from aircraft to ground station, the bounds are 150 and 250 s, respectively.

It should be observed that the data link exhibits a higher availability than voice communications due to the use of digital transmission and forward error control. Where voice channel only offers an 80% availability, HFDL reaches 95% availability with coverage from two HF stations and more than 99% availability with coverage from three or four HF stations.