Flight Trial Demonstration of Seamless Aeronautical Networking

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Abstract: This article presents the in-flight demonstration of a new integrated aircraft communications system combining legacy and future radio technologies. This system, developed and validated under real environmental conditions during flight trials, integrates all the aeronautical service domains within a common IPv6-based aeronautical network. The flight trials were held within the framework of the European SANDRA project at Oberpfaffenhofen, Germany, in June 2013. The presented outcomes emphasize the flexibility and scalability of the developed network and demonstrate the seamless service coverage of the given architecture across different airspace domains[1].

Keywords: Flight trials, Seamless Aeronautical Network, IPv6, AeroMACS, BGAN, VDL2.

[1]The material in this paper was presented in part at DASC 2013, Syracuse, NY, USA

1. Introduction

Aeronautical communications are currently facing a continuous increase in capacity demand. This ceaseless request for more communication capacity is because of the constant growth in the number of passengers and, thus, aircrafts, which are expected to double by 2035 [1] and the introduction of new aeronautical communication services with high data volume demand. The latter comprise, among others, new operational safety critical services, such as 4D-trajectory and nonsafety critical services like wireless in-cabin connectivity for passengers. To cope with this high demand in communications capacity, part of the ongoing research aims at developing new concepts and technologies for future aeronautical communications (like the European SESAR Joint Undertaking program [2] and the FAA Next Generation Air Transportation System (NextGen) [3]) with a strong emphasis on the development of new link technologies, such as the terrestrial L-band Digital Aeronautical Communications System (L-DACS) link [4] and the European Space Agency (ESA) Iris program [5].

The introduction of new digital communication links is of paramount importance in the aeronautical sector as the existing Air Traffic Management (ATM) communication infrastructure already operates close to its maximum capacity [6]. Although the new systems will eventually replace the legacy communication systems, there will be a lengthy period in which an aircraft will be fitted with all of the systems for global interoperability. Hence, there is a need to integrate legacy and future data links into one large seamless aeronautical network to serve future communication demand.

The design, development, and validation of such a seamless network correspond to the focus of the European-funded research project SANDRA (Seamless Aeronautical Networking through integration of Data links Radios and Antennas) [7], which integrates different communication links (legacy and future data links) and networks (such as ATN/OSI or ATN/IPS) with all the aeronautical service domains (ATS, AOC/AAC, and APC) in a safe, high-performance, and cost effective way

through IPv6 as the unification point. The development of the entire corresponding ground network infrastructure is also part of the SANDRA architecture. The validation of the latter was realized by performing flight trials on the airport of Oberpfaffenhofen, close to Munich, Germany [8]. This paper gives an overview of the outcomes of the first SANDRA flight trials with a strong emphasis on the seamless handovers that were carried out between legacy and future data links, namely, VDL2, BGAN, and the newly developed AeroMACS [9], thus proving the flexibility and scalability of the SANDRA network. The seamless service coverage aspect of the SANDRA architecture was demonstrated by the successful test of various applications in all aeronautical service domains.

The rest of the article is organized as follows. The SANDRA concept is introduced, followed by the details of the overall system setup and the most relevant components. The flight trials and the main results regarding handovers, network technologies, and used applications are presented.

Glossary

AAC	Airline Administrative Communications	BGAN	Broadband Global Area Network by Inmarsat
AeroMACS	Aeronautical Mobile Airport Communications System	CLNP	Connectionless Network Protocol
AOC	Airline Operations Center	IDRP	Inter-Domain Routing Protocol
APC	Aeronautical Passenger Communication	IPS	Internet Protocol Suite
ATN	Aeronautical Telecommunication Network	OSI	Open System Interconnection
ATS	Air Traffic Service	VDL2	Very high frequency (VHF) Digital Link mode 2

2. The SANDRA Concept

The vision of SANDRA is the integration of aeronautical communications systems by using well-proved industry standards to enable a cost-efficient global provision of distributed services. SANDRA system is considered as a “system of systems” addressing four levels of integration: service, network, radio, and antenna.

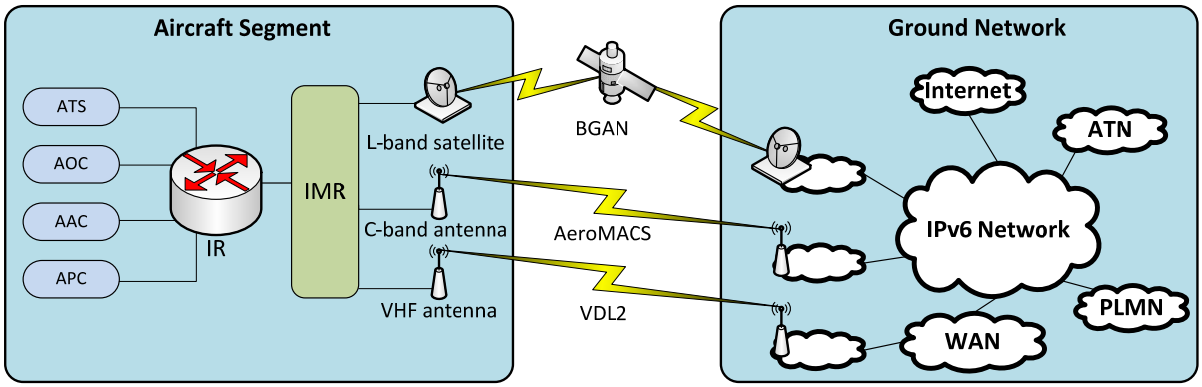


Figure 1. SANDRA flight trial network architecture.

With respect to the communications network, SANDRA spans across two segments—the aircraft and ground segments, as shown in Figure 1. The aircraft segment for the flight trials contains the main functional components: the integrated router (IR); the integrated modular radio (IMR); and the antennas consisting of a satellite L-band antenna (BGAN), a VHF-band antenna, and a C-band antenna for AeroMACS. Details about the SANDRA ground network are given in the following section.

3. System Setup

The system setup of the SANDRA flight trials is composed of two major segments: the airborne segment and the ground infrastructure.

3.1 Airborne Segment

The SANDRA airborne system was integrated in an Airbus A320 as displayed in Figure 2.

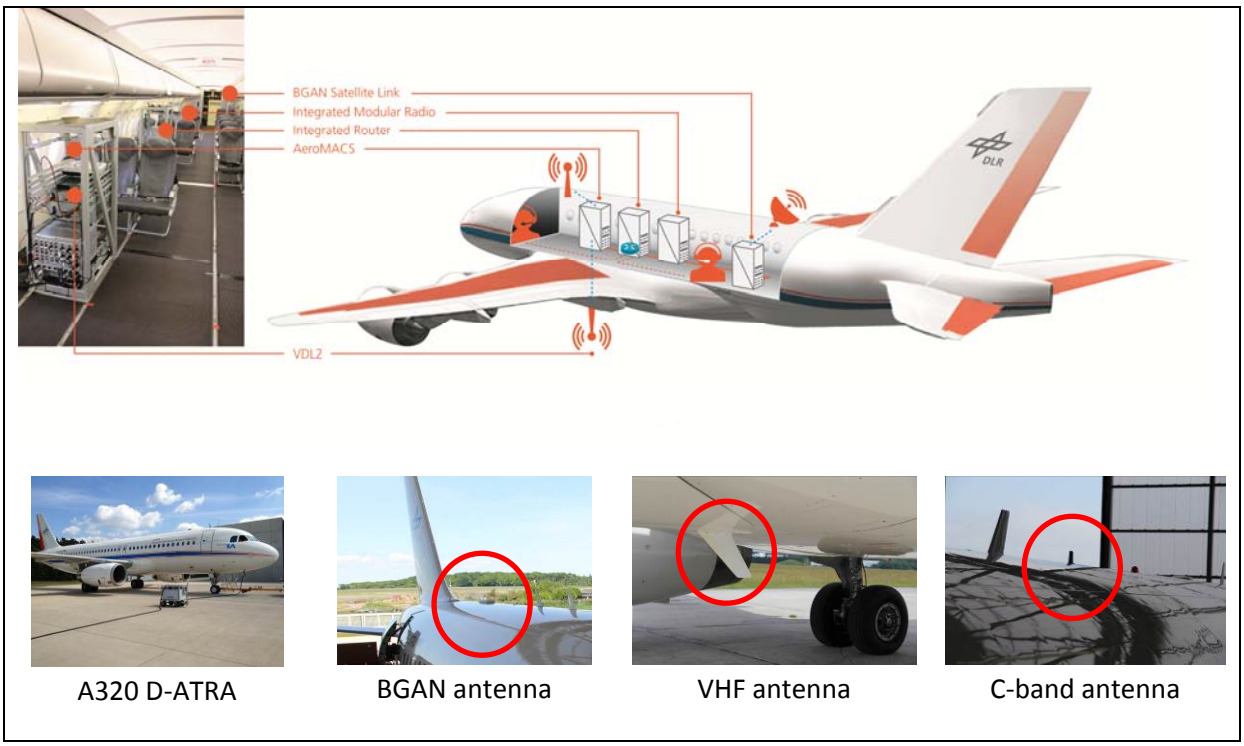


Figure 2. SANDRA airborne system installed in an A320 including the experimental antennas.

As for the data links, three different radio technologies were integrated in the aircraft: BGAN, VDL2, and AeroMACS. The aircraft was already equipped with a BGAN and a VHF antenna (used to test VDL2), which were located on top, at the rear of the fuselage, and in the middle, below the fuselage, respectively. The AeroMACS C-band antenna was especially mounted on top of the fuselage for the SANDRA flight trials. The inline figures of Figure 2 show the positions of the BGAN, VHF, and AeroMACS antennas on the fuselage of the aircraft.

To be integrated in the aircraft, the SANDRA airborne system was divided into four separate racks containing different pieces of equipment as illustrated in Figure 2. The distribution of equipment within the racks was based on the different functionalities, whereas the locations of the racks within the cabin were defined based on the positions of the antennas on the aircraft's fuselage.

The racks were organized as follows. The first rack contained the integrated router and the connectivity to the different end-user systems. The second rack was equipped with the two integrated modular radio processing platforms, thus representing the link between the IR and the different RF equipment (one IMR used as redundancy backup, cf. IMR-PC2 in Figure A.). The third rack was fitted with the RF units for the VDL2 and AeroMACS data links. Finally, the RF components that handle the BGAN satellite link were located in the fourth rack at the rear of the cabin. To maximally reduce the antenna cable losses, the third and fourth racks were placed in the cabin right below the respective antennas.

3.2 Ground Infrastructure

The core part of the SANDRA ground infrastructure was located at Oberpfaffenhofen, Germany. It is composed of all the IP-based networking components, such as the access router and the home agent. The home agent includes functionalities like IPsec (IPv6) to provide authentication and integrity and the NEMO protocol [10] to guarantee mobility to the airborne terminal. Furthermore, the home agent provides global reachability accessing the mobile node via the home address during handover from/to AeroMACS to/from BGAN when attachment point changes from one access network to another. The IPsec integrates an IPv6-over-IPv4 transition mechanism, entitled NeXT [11]. The access router also provides the router advertisement messages (ICMPv6) required by NEMO on the integrated router. This message is part of the neighbor discovery protocol (NDP, RFC 4861). The SANDRA network provides connectivity not only to the different ground-end systems but also to the ATN, the Internet, and the Public Switched Telephone Network (PSTN, for passenger communication). It enables ATS (communication with air traffic control (ATC)) and AOC services (business communication of the airline) as well as APC (e.g., for Internet access and mobile telephony) and airline nonoperational services (AAC).

For the ground infrastructure of the data links two different base stations were specifically installed for the SANDRA flight trials: a VHF ground station (VGS) and an AeroMACS base station. The latter was installed on top of a hangar building overlooking the Oberpfaffenhofen Airport. Connectivity between this base station and the SANDRA laboratory was established via a VLAN. The antenna used for the AeroMACS base station was a directional antenna (90°) with a focus on the aircraft's parking position. Furthermore, car tests were carried out at the Oberpfaffenhofen Airport to estimate the received signal level from the AeroMACS base station. A C-band antenna was mounted on the roof of a research vehicle. The signal level could be estimated on the runway, taxiing path, and parking position of the aircraft using a spectrum analyzer.

Finally, for the ATN/OSI ground infrastructure, a VGS for VDL2 was installed on the roof of the SANDRA laboratory close to the airfield, although the ATN/OSI ground-end system was located at Montreal, Canada, and connected to the SANDRA laboratory via a wide area network (WAN). The satellite connection was made over the BGAN satellite network. Further insights on the SANDRA ground infrastructure and the overall SANDRA test bed can be found in [12].

The SANDRA flight trials occurred from 24 to 26 of June 2013 at the Oberpfaffenhofen Airport (EDMO), Germany. This airport consists of one single runway. The parking position of the aircraft was in direct line-of-sight (LOS) with the AeroMACS base station and the VGS.

4. Results of Flight Trials

4.1 Description of Flight Sorties

Six sorties were made in 3 days with the D-ATRA aircraft at a rate of two flights per day. The focus of the first day was mainly to evaluate the correctness of data transmission over the air for each of the three data links. Once the links were operational, the flight trials of the second and third days aimed at validating the SANDRA concept by performing a set of scenarios that were previously

identified. To do so, various applications ranging from ATS over AOC, AAC, and APC services were tested onboard the aircraft.

On average, each sortie lasted roughly 90 minutes including taxiing, take-off, and landing phases. The scenarios were performed onboard during the 45 minutes of cruise. For each sortie, the aircraft was flew over the Oberpfaffenhofen Airport and continued its route until the VHF connection was lost and turned around to fly back over the airport. Once out of the VHF coverage, the system seamlessly switched over to BGAN / L-Band with no loss of traffic in the scenario under test. This allowed testing the seamless functionality of the SANDRA concept.

4.2 Seamless Aeronautical Networking Analysis

4.2.1 Seamless Layer 3 Handover

Whenever a change of traffic routing policy involving two different data links occurred, a handover was performed. During the flight trials, handovers were performed between all the three link technologies in both directions (e.g., BGAN to VDL2 and VDL2 to BGAN) and also between some combinations of different quality of service contexts within the same technology (BGAN background to BGAN streaming). Additionally, the handovers were classified depending on the triggering condition. One type of handover was the “IMR triggered handover,” initiated by the integrated modular radio when the aircraft was moving (or was already) out of coverage of one of the available links. The other type, the “IR triggered handover,” was a handover caused by an automatic or manual change of the routing on the integrated router based on a policy (e.g., changing to a newly available and preferred link).

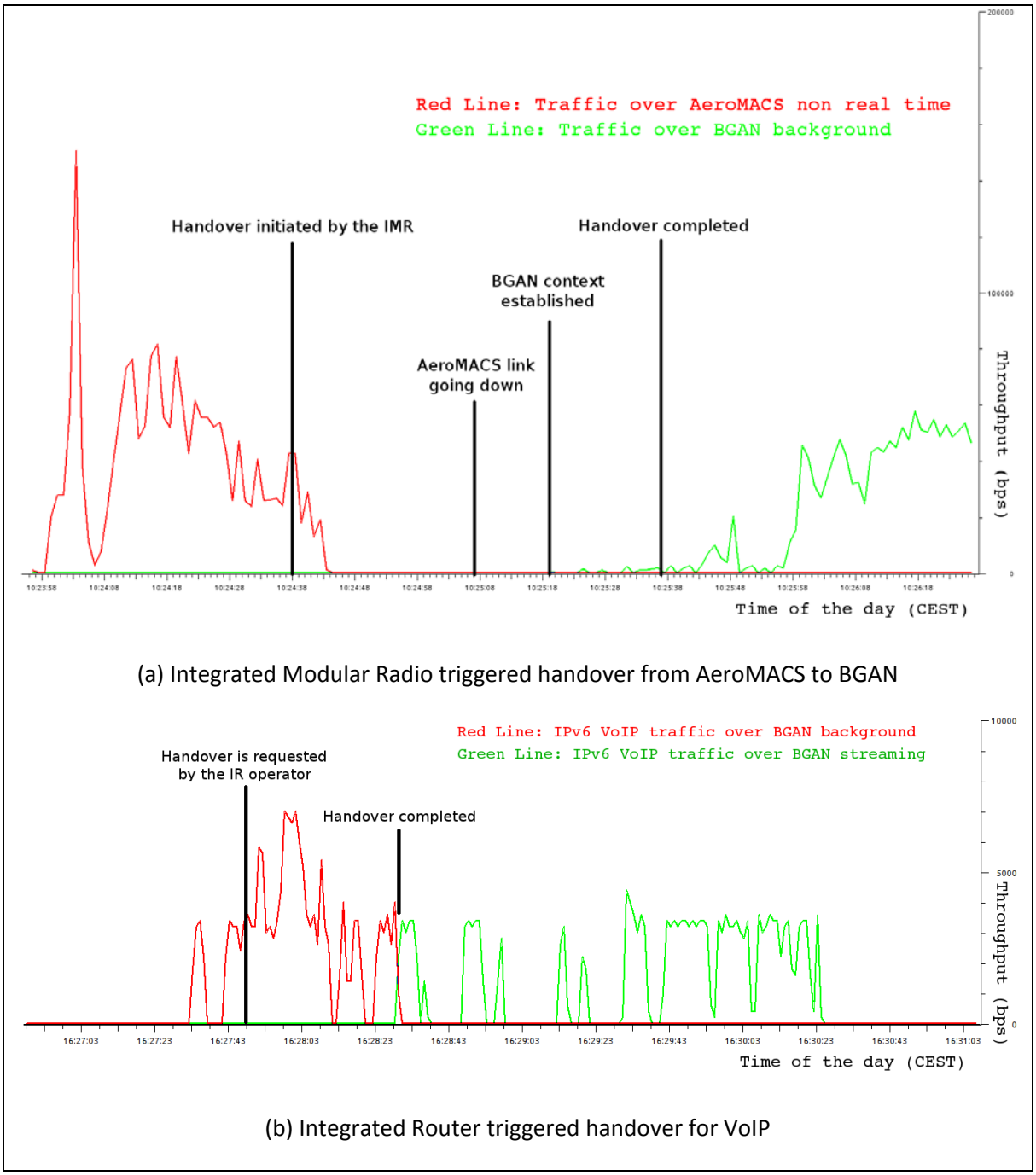
To test the “IMR triggered handover,” an AeroMACS context was open while the aircraft was in the parking position. Once set, traffic was generated from the end systems to put some load on the link. Then, the IMR was told that the aircraft was changing from a “standing” position to “*en*

route." Because AeroMACS is not available while the aircraft is cruising, the IMR initiated the procedure to open a new BGAN context and notified the IR of the upcoming change. Figure 3(a) shows the handover and how traffic is sent over the BGAN again after the handover is completed.

An "IR triggered handover" can be observed in Figure 3(b). Initially, all traffic is sent over a BGAN background context. Although this best-effort type of service is good enough for applications like browsing or e-mailing, it is not suitable for jitter-sensitive applications like voice-over-IP (VoIP). Therefore, a manual change of policy routing was performed. Instead of interrupting the traffic on the request, the traffic is routed through the new context only after this was completely established, thereby avoiding an interruption of the communication. The VoIP call members did not notice any loss of communication, and in fact, no packets were lost during the handover, and only one packet suffered reordering.

It should be noted that the "IMR triggered handover" is performed when a link-in-use unexpectedly goes down. The communication is temporarily interrupted while the connection with the new link is established. "IR triggered handovers" are carried out while the link is still active, opening a context with a different link and modifying the routing only when new link is operational.

After disabling AeroMACS data link (step (1) in Figure 3(a)) the content request by the IMR from the BGAN network takes around 30sec. Now, the care-of-address can be provided towards the IR. Then, IR can initiate establishment of the IP connectivity with the ground (NeXT, NEMO, and policy routing update). Improvements in all these handover procedures can be seen here.



(a) Integrated Modular Radio triggered handover from AeroMACS to BGAN

(b) Integrated Router triggered handover for VoIP

Figure 3. Triggered handover performances.

4.2.2 Seamless Layer 2 Handover

The IMR, which represents the data link and physical layer of the OSI stack, consists of the different radio protocol stacks (AeroMACS, VDL2, and BGAN), includes an adaptation layer called joint radio resource manager (JRRM) that is responsible for managing and controlling the underlying radios in a uniform and consistent manner, and provides a single interface to the network layer (cf. Figure A).

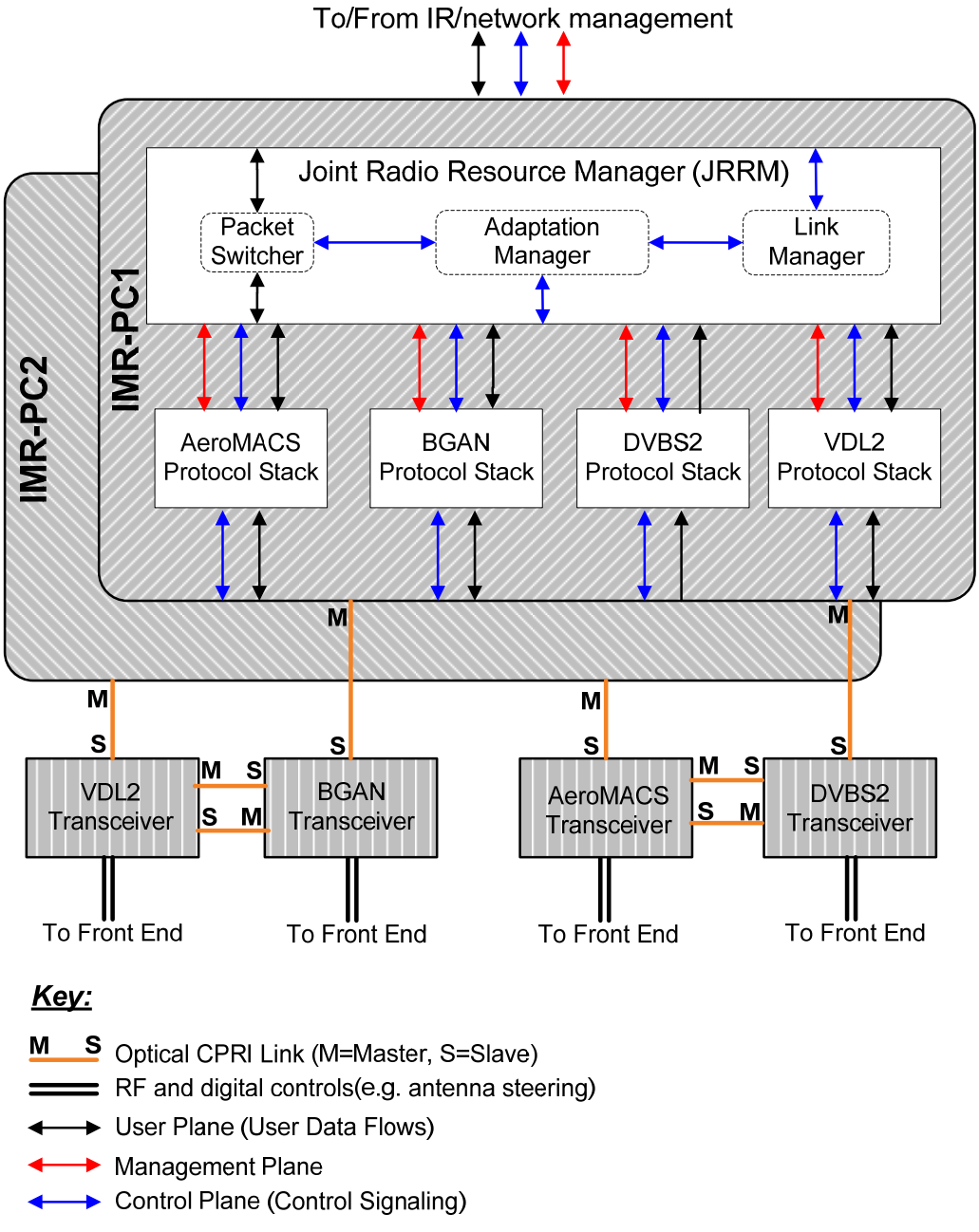


Figure A. Principle architecture of the IMR.

To increase the assurance of the IMR, there are two JRRMs running simultaneously with one on each IMR processing platform, IMR-PC1 and IMR-PC2, respectively. At any time, there is only one JRRM acting as the master and is in charge of all the processing, whereas the slave JRRM keeps on synchronizing with the master. Different time recordings for the hot swap process (when the master JRRM was terminated and the slave JRRM was swapped as the new master) could be done during the flight trials. The data-tunnel switch time indicates the time window in which data cannot be transmitted. This time varied between 170 and 184 ms. The overall switch time is the period starting from when the slave JRRM detects a failure of the master until all submodules complete the switching process. Here, the maximum recorded time was 286 ms, and the minimum time was 180 ms. Because of the multi-core and multi-threading programming techniques, there is not much difference between the time required for processing single or multiple data tunnels.

When the radio stacks were running on the same processing platform with the new master JRRM, it took slightly longer time for the switch process to complete because the computing resources were shared between the JRRM and radio stacks. Similarly, the data tunnel traffic load affected the switching time: the heavier the user traffic, the longer the switching time.

Figure 4 shows the time required for session establishment from randomly selected BGAN and AeroMACS sessions during the flight trial. The session establishment time is the overall time taken from the reception of the session open request until the data tunnel is completely ready for data transmission. To express the processing time required by the JRRM more precisely, the processing time in the JRRM only measures the time used within the JRRM modules by excluding the layer-two processing time of radio stacks, such as ranging, registration, or attachment time. The minimum session establishment time observed was 3.02 s when the satellite terminal had already been registered and attached to the network before the session open request. The maximum time observed was 22 s when a fresh network registration and attachment was to be done to setup and activate the packet data protocol (PDP) context for the open request. On the other hand, establishment of the AeroMACS session is quicker; it takes less than 1 s to complete a data

connection with the ground station. However, processing time used for session establishment within the JRRM for BGAN and that for AeroMACS have the same order of magnitude despite the big overall difference in their end-to-end connection establishment owing to the fact that JRRM treats all the waveforms equally and in a uniform way.

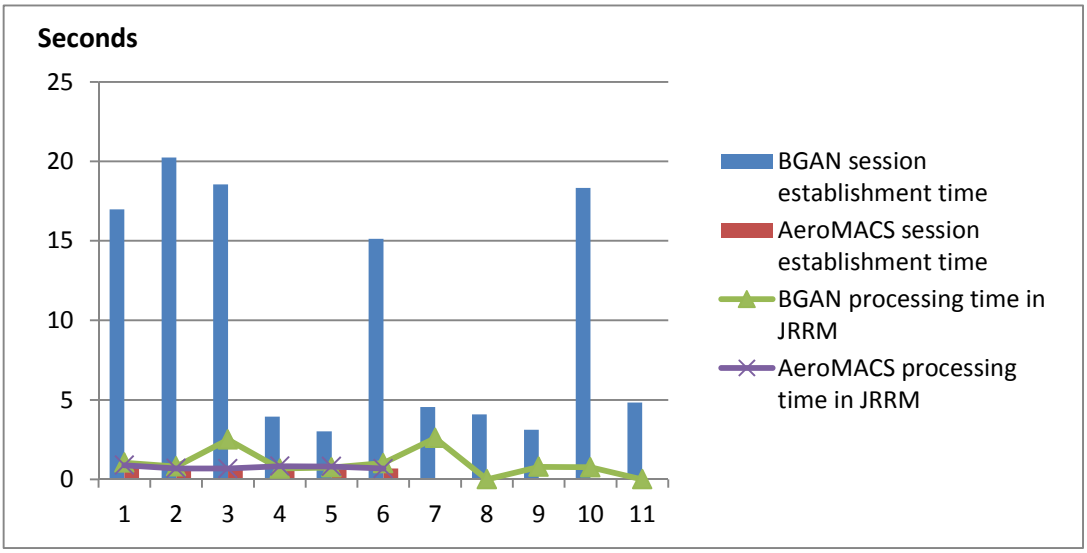


Figure 4. Session establishment time.

4.2.3 ATN/OSI over IP-SNDCF

The use of IP subnetwork dependent convergence function (SNDCF) enables the ATN/OSI upper layers and network (CLNP-IDRP) protocols to be conveyed over the IP protocol. This allows IP-based networks to be used for providing the underlying ATN subnetwork links between the ATN-routing entities. It was decided to experiment on the use of IP-SNDCF on the aircraft (whereas today it is only used on ground) and thus on a mobile system. The objective was to assess if the ATN/OSI CLNP packets could be conveyed over VDL2 (as done today) and over the SANDRA broadband radio-IP links in a seamless way. The advantage of a mobile IP-SNDCF is that avionics and ground stations can implement a single (or multiple but standardized) SNDCF for all mobile communication technologies instead of having different interfaces for each technology, which is the case at present.

A prototype mobile IP-SNDCF module was developed and integrated on existing ground architecture and on the aircraft, cf. Figure B. This allowed demonstrating end-to-end ATN/OSI communications over VDL2 and SANDRA mobile IP implementation over BGAN and AeroMACS [13].

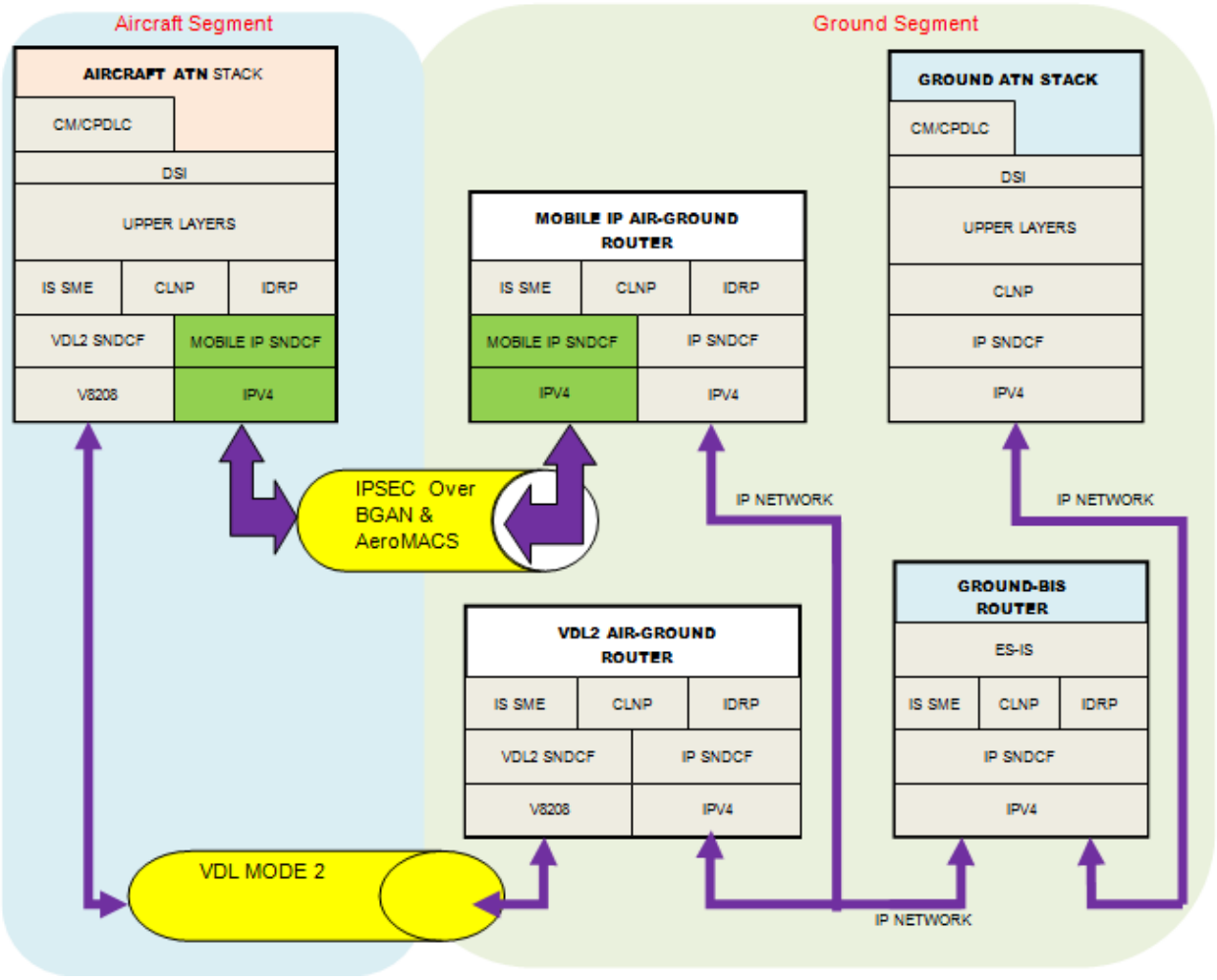


Figure B. Principle architecture of ATN/OSI over mobile IP-SNDCF.

4.3 Aeronautical Service Coverage

Table 1 reveals the different applications that were successfully tested on ground and in the cruising phase to validate the SANDRA concept. As can be seen in Table 1, applications from all the different aeronautical service domains were tested during the flight trials, thereby emphasizing the seamless service coverage of SANDRA. As to the airborne end-system, most of the applications were

tested using a notebook or tablet directly connected to the integrated router either via an Ethernet cable or via in-cabin wireless local access network. Their counterparts on the ground had various locations, such as the SANDRA laboratory or the different internet servers. In the following section, various applications of different service domains concerning safety relevant data, such as voice communication in the cockpit, airline operations services, and cabin communications, are highlighted.

Table 1. List of applications tested during the SANDRA flight trials.

Application	**Domain**	**Airborne end-system**	**Ground end-system**	**Ground end-system location**
AMBEATC10B VoIP	ATS	VoIP HW	VoIP HW	SANDRA lab
CPDLC ATN/OSI apps.	ATS	CMU Notebook	ATN ES	Montreal
Generic CPDLC tool	ATS	Notebook	Notebook	SANDRA lab
Electronic flight information bulletin	AOC	Notebook	Server(s)	Internet
Web chart application	AOC	Notebook	Server(s)	Internet
Web flight planning application	AOC	Notebook	Server(s)	Internet
Electronic flight folder	AOC	Notebook	Notebook,	SANDRA lab
Flightstrips	AAC	Notebook	Notebook	SANDRA lab
Generic arrival/departure manager	AAC	Notebook	Notebook	SANDRA lab
Telemedicine	AAC	Telemedicine tablet	Telemedicine server	Internet
VoIP call	APC	VoIP mobile	VoIP Handset	Internet
Web browser	APC	Tablet	Web server	Internet
Email	APC	Tablet	Email Server	Internet
Skype™	APC	Tablet	Skype™	Internet

4.3.1 AMBEATC10B VoIP

The AMBEATC10B VoIP is an experimental hardware voice-over-IP appliance based on the AMBE ATC 10B vocoder circuit board. This is currently the only digital vocoder certified for air traffic control. The circuit board is integrated with a micro-controller and installed in a rack-mountable case with a push-to-talk button. The micro controller board runs a customized version of the Linux operating system that reads/writes voice samples from the vocoder board and sends/receives them over the SANDRA network using the user datagram protocol (UDP)/IPv6. Both the airborne and the ground appliances were equipped with commercially available ATC headsets.

The quality of service delivered by the SANDRA network for VoIP applications was evaluated using the AMBEATC10B VoIP appliance according to ITU recommendation P.80 “Methods for Subjective Determination of Transmission Quality.” ITU P.80 defines a conversation opinion test. Two subjects engage in a set of previously arranged domain-specific conversations and rate them according to a defined scale. In addition, the subjects were interviewed to better understand the rating. In the case of the SANDRA evaluation, the conversations were constructed from the air traffic control simulation speech corpus [14]. Each conversation comprised six ATC phrases exchanged by the subjects. After the conversation, each subject was asked to provide an opinion on the transmission quality (excellent = 5, …, bad = 1) and to indicate any difficulties in understanding the conversation partner (yes = 1, no = 0).

The SANDRA evaluation composed of four different speakers and 65 conversations (i.e., 390 phrases exchanged) was limited by the flight time and the number of personnel available in the aircraft. The participants were familiar with the transmission quality offered by the DSB-AM systems. The subjective rating of the voice quality should therefore be understood as relative to the established ATC voice systems.

Four of the 65 conversations were interrupted by reconfigurations of the data links. Handovers from the AeroMACS link to the satellite link were seamless and generally not noticed by

the conversing subjects. However, the smaller round-trip delay of the AeroMACS system when compared with the satellite link was perceived. The users noticed occasional packet loss on the satellite link by missing the syllables in the conversations, but it was not perceived as a great problem.

The mean score over all the conversations was 4.33 (excellent = 5, good = 4) on the airborne side and 3.93 (fair = 3) on the groundside. The perceived lower audio quality of the ground users can be explained by the background noise in the aircraft that was included in the transmission. On the aircraft, the background noise was attenuated by the headsets, providing the airborne user with a clear reproduction of the ground signal recorded in a quiet room.

4.3.2 CPDLC ATN/OSI Application

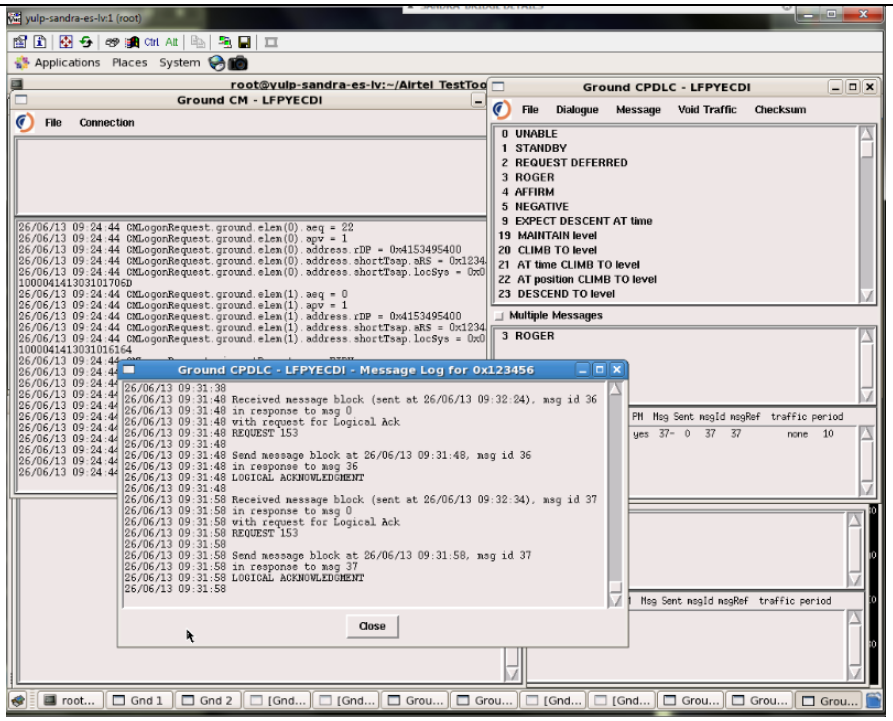
For the controller–pilot data link communications (CPDLC) ATN/OSI application, the ground-end system was located in Montreal, Canada. During the in-flight test of this application, a connection between the VGS on the ground and Montreal was established over the ATN/OSI ground network. The transmission of CPDLC messages was made over the VDL2 link. When the handover with BGAN (or AeroMACS) occurred, an IP connection through the SANDRA ground network was established between the airborne and the ground-end system in Montreal. The path for CPDLC messages switched thus from the ATN/OSI ground network to the IP-based SANDRA ground network. Figure 5(a) gives an example of the CPDLC request exchanged every 10 s during the first test on the 26th of June. One can notice that the LACK was generally received in 1 s (in IP over AeroMACS).

Context management (CM)/CPDLC messages were routed seamlessly over one medium or the other, without any impact on the upper layers. During the flight tests, the IP path (BGAN or AeroMACS) was given priority, and whenever both the VDL2 and the IP paths were available at the same time, traffic was automatically routed over the IP path. When the IP path became unavailable, traffic fell back to using the VDL2 path.

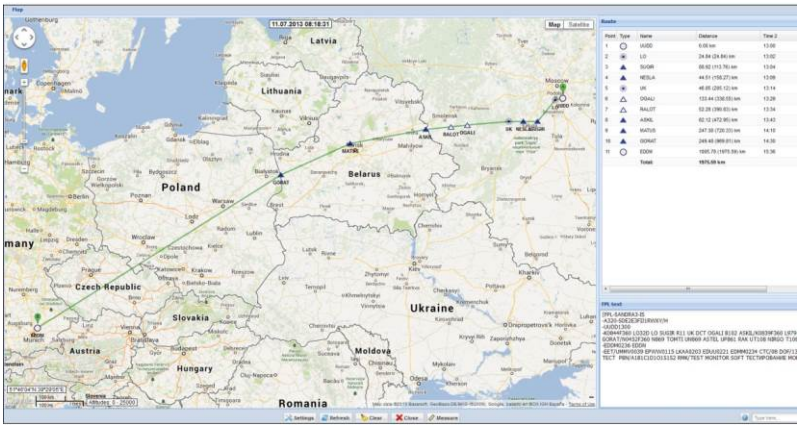
4.3.3 Airline Operational Services

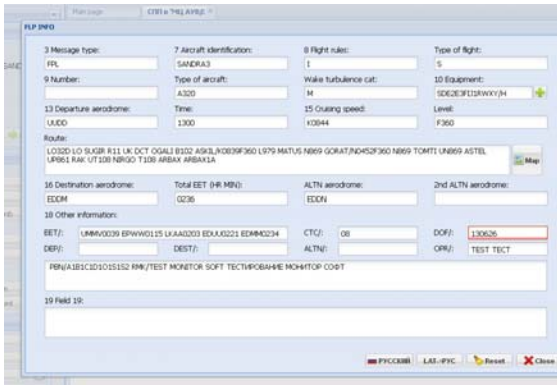
Two applications that pertain to the operational service domain of an airliner are described in this section. These applications were integrated and tested during the flight trials. The first application aims at providing the crewmembers with the current changes that are taking place in the airspace and in airports with reference to the scope of a particular flight. The application receives basic flight details from a user and then requests for all the relevant notice to airmen (NoTAM) messages from a central server. The output data are presented in the ICAO format. The second application emulates a Web service for both basic flight planning and submission of the flight plan request to the state ATM authority. Along with the other features, this application provides a digital map with details of the current aeronautical situation, automated route selection, and numerous flight plan checks.

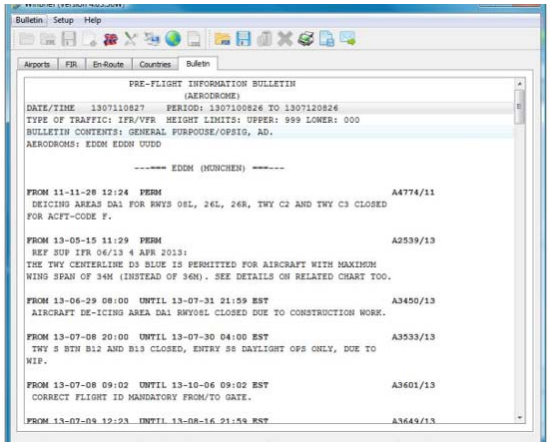
A dedicated route, that is, UUDD (Domodedovo, Moscow) → EDDM (Munich), was first selected for such software tests as depicted in Figure 5(b). The corresponding flight plan was successfully created and submitted. Then, a positive response (approval) was received from the ATM service. Finally, all necessary NoTAMs regarding the chosen flight were requested and received. All communications of both applications took place during the taxiing and cruise phases. Despite some loss of packets and the consequent repeated requests in the TCP/IP stack (which was not seen at the application level), the software managed to communicate with the ground successfully.



(a) CPDLC request exchanges







(b) Web flight planning application with ICAO FPL form submitted and NOTAMs for UUDD-EDDM at time of flight trial

Figure 5. Examples of the demonstrated applications.

4.3.4 Cabin Applications

Furthermore, real-life passenger-cabin applications were tested while in flight. This involved a number of passenger scenarios including surfing the Internet and sending and receiving emails through their Internet portal. With the aid of smart phones, those in the air demonstrated social media posting and messaging as well as Skype™ video and audio calls all through the SANDRA radios. A patient monitoring unit was also demonstrated successfully for the use of the crew, whereby a crewmember and a doctor on the ground can simultaneously monitor the vital signs of a passenger while in constant audio communication through the SANDRA radio system. As part of the demonstration the unit's blood pressure monitor and pulse monitor were attached to one of the test engineers in flight. Patient monitoring units provides additional medical support to the cabin crew when it is needed most.

4.3.5 Performance of Applications over Future Data Link

Finally, through a closer look of the new integrated AeroMACS nonlegacy data link, it was observed that the end-to-end connectivity was affected not only by AeroMACS but also by all other networking systems (integrated router, integrated modular radio, access router, home agent, etc.). This was verified using the internet control message protocol (ICMP) pings that measured the following delays: minimum delay = 33.314 ms, maximum delay = 265.054 ms, average delay = 76.823 ms, standard deviation = 32.172 ms, and a packet loss rate measurement of below 0.5%.

Different applications successfully tested using AeroMACS connectivity are as follows:

-AMBE ATC VoIP, both over non-real-time and real-time profiles, with an average of 27 kbps throughput during voice transmission;

-ATN/OSI over IP-SNDCF traffic, with an average throughput of 0.5 kbps with peaks of 2.5 kbps; and

-electronic flight folder file transfer protocol (FTP) traffic, with forward link traffic peak close to 1 Mbps, and an average traffic of below 300 kbps.

5. Conclusions

In this paper, the outcomes of the flight trial of a new integrated aircraft communications system were presented. Developed within the framework of the SANDRA project, this system was integrated in an Airbus A320 and tested in real flight conditions in June 2013 at the Oberpfaffenhofen Airport, Germany.

During these flight trials, the two key features of the SANDRA concept were demonstrated. On the one hand, the seamless service coverage of the SANDRA architecture across different airspace domains was shown. By keeping IPv6 as the unification point, it was proven that this system integrates a full range of aeronautical applications (ATS, AOC/AAC, and APC).

The second key feature of the SANDRA concept that was demonstrated during the flight trials was its global interoperability between legacy (VDL2 and BGAN) and future data links (AeroMACS). This was realized by performing, first, a handover on the ground between VDL2 and AeroMACS data links and, second, a handover while flying between the VDL2 and the BGAN satellite links (for both cases, handovers were performed in both directions). Transparent to the end-user, these handovers have proven the interoperable and scalable aspects of the SANDRA network, which can switch reciprocally between legacy (non-IP) and future (IP) data links.

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