SANDRA PROJECT FINAL REPORT

Publishable Summary

Grant Agreement number: 233679

Project acronym: SANDRA

Project title: SEAMLESS AERONAUTICAL NETWORKING THROUGH INTEGRATION OF DATA LINKS, RADIOS AND ANTENNAS

Funding Scheme: Collaborative Project (CP) - Large-scale integrating project (IP)

Period covered: **from** September 2009 **to** December 2013

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1. Executive summary

Digital communication systems are an everyday routine for more and more passengers, but pilots are largely cut off from this development. This is because, up until now, they have had to communicate using a completely separate system that is primarily analogue. With smartphones, we have been used to surfing the Internet when we are travelling, using the cheapest possible connection available, be it WLAN, the mobile network or via Bluetooth. It is precisely this flexibility that is also required in the new approach to aircraft communications.
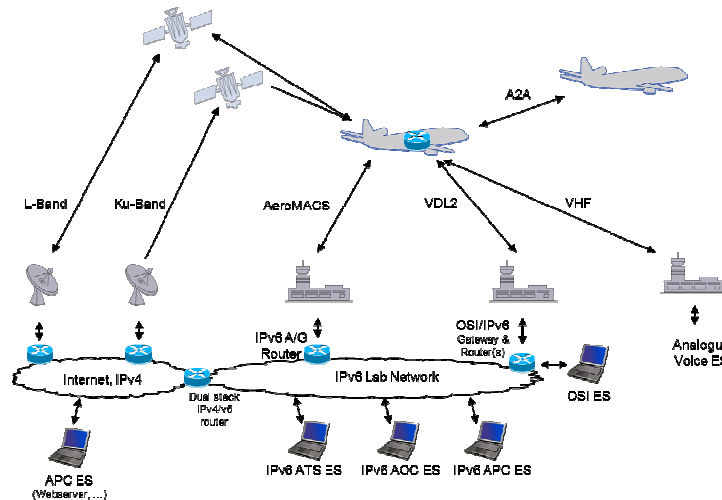

Figure 1: SANDRA Aeronautical Networking environment

SANDRA project has studied, implemented and demonstrated in flight a new system that will lead pilots into the digital world of the 21st century. A single device transmits communications with the ground and via satellite, digitally at high speed. Detailed information, such as the weather, flight plan or the traffic situation can therefore be exchanged between the tower and the aircraft quickly and reliably, increasing the air traffic safety. The novelty of the SANDRA approach consists in pursuing integration at different levels:

- service integration: integration of a full range of applications (ATS, AOC, AAC, APC);
- network integration: an Integrated Router (IR) based on Interworking of different radio access technologies through a common IP-based aeronautical network whilst maintaining support for existing network technologies (ACARS, ATN/OSI, ATN/IPS, IPv4, IPv6);
- radio integration: design and test of a prototype Integrated Modular Radio (IMR) system capable of interfacing with sufficient bearers to prove all of the concepts developed in the SANDRA global system architecture (Inmarsat SBB class 6/7, Ku DVB-S2, AeroMACS, and VDL Mode 2);
- antenna integration: design, test and implementation of an integrated SatCom antenna prototype (Ku/L-band) using novel optical beam forming techniques, as key enabler for a hybrid data link system using different bearers for inboard and outboard communications
- AeroMACS: definition, design and validation of a technical profile and network architecture for an AeroMACS based airport wide area network, to enable improved information

distribution and provide lower cost, as well as safer and more efficient airport surface operations
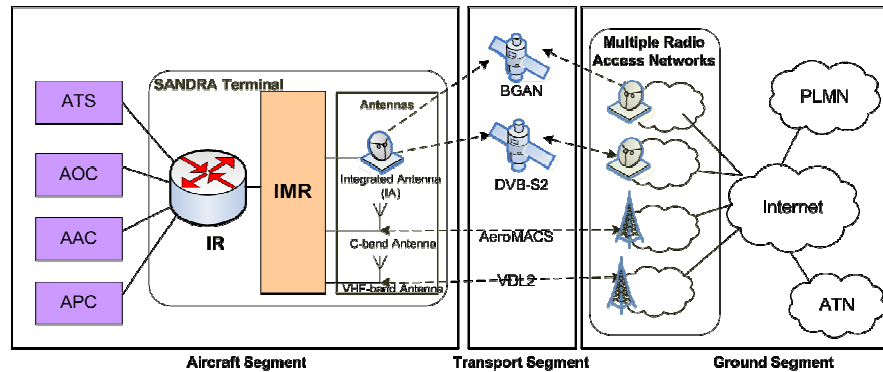

Figure 2: SANDRA main functional blocks

All the prototypes developed in SANDRA have been integrated in a test bed, aiming at validating the SANDRA concept up to TRL 5/6. Laboratory tests and in-flight trials have been carried out to show and prove the acquired TRL and the benefits of the integrated SANDRA approach in terms of adaptability and re-configurability with respect to existing aeronautical communications systems based on existing network and access technologies.

2. Project context and objectives

The overall air transportation sector is currently under significant stress. With the demand in aircraft operations expected at least to double by the 2025 timeframe, there are well-founded concerns that current air transportation systems will not be able to accommodate this growth. Existing systems are unable to process and provide flight information in real time, and current processes and procedures do not provide the flexibility needed to meet the growing demand. New security requirements are affecting the ability to efficiently move people and cargo. In addition, the growth in air transportation has provoked community concerns over aircraft noise, air quality, and air space congestion. Summarizing: by using the current tools and procedures, the effective increase of air traffic, which is already approaching its limits, will be basically limited.

State of the art

Aeronautical communications can be separated in two areas: one handles the safety and regularity of flights communications, namely the Air Traffic Control (ATC) and Airline Operational Control (AOC). The other is related to the non-safety critical services which includes Airline Administrative Communications (AAC) and Aeronautical Passenger Communications (APC). For all these kinds of communications today exists dedicated solutions with limited performance but no single integrated global network covering all demands and requirements.

Therefore, all systems are operating in parallel using their own cost-intensive equipment per aircraft and may not cover all areas. The completed European project NEWSKY [1] investigated the feasibility of a heterogeneous aeronautical communications network and developed a preliminary design for integrating different communications systems and applications to a single network. Also the ACAST project of the NASA Glenn Research Center [2] investigated future aeronautical

communications infrastructure technology for such a network in 2008. The Federal Aviation Administration (FAA) and EUROCONTROL agreed that a paradigm shift will occur in the operating concept and the prime mode of communication exchanges will be based in data exchanges rather than voice communication as it is today. Furthermore, a service-oriented avionics architecture is envisaged [3].

Two programs were launched simultaneously in Europe and in the US to develop these new concepts. The European ATM Master Plan addresses the future of ATM in Europe over the next decades and forms the basis for the work program of SESAR. The Single European Sky ATM Research Program (SESAR) was initiated and is funded by the European Commission, EUROCONTROL and aeronautical industry. Also in the US, the FAA implemented the Next Generation Air Transportation System (NextGen) following the agency's vision of an evolution from a ground-based system of air traffic control to a satellite-based system of air traffic management.

Trends in Aeronautical Communications

Focusing on communications related aspects, the following high-level requirements have been identified, in order to allow future systems to be compatible with the expected air-traffic increase:

- shifting from the current voice communication to data communication to provide an additional means of two-way communication for air traffic control clearances, instructions, advisories, flight crew requests, and reports;

- establishing a System Wide Information system (SWIM) to provide a single infrastructure and information management system to deliver high quality, timely data to many users, and applications. SWIM will reduce data redundancy and better facilitate multi-user information by securely connecting all the ATM stakeholders;

- pilots situation awareness shall be improved, also thanks to ground SWIM extensions to aircraft domain;

- capacity at airports, today one of the main limiting structural factors, shall be increased;

- Airline Operational and Administrative air-ground data traffic shall strongly increase for efficient airline operations (maintenance data, passenger related services, etc.);

- passengers and cabin communications systems shall be further developed;

- safety critical applications shall need diverse means to reach ground for global availability and higher reliability;

- a simplification of on-board network architecture shall need convergence of protocols and interfaces

To cope with these issues, new communication concepts are being developed but still often separately by SESAR/NextGEN for ATC/AOC and by Airlines in the AAC/APC domains. In order to provide the new services required to meet the above requirements several additional radio links have been proposed by SESAR and elsewhere.

However, this represents a considerable extra burden of size, weight, complexity and cost in avionics for aircraft to carry, should the new radio links be implemented in stand-alone equipment,

as has been traditionally the case in avionics. Moreover, although it has been suggested that the new systems will eventually replace the legacy communications systems, the likelihood is that there will be a lengthy period where aircraft will be fitted with all of the systems for global interoperability. This is the forecast expressed by SESAR, and the additional airborne equipment required during this transition phase severely threatens the realization of the future communications vision.

Hence, a different approach aiming at a broader level of integration is needed to achieve the required increase of capacity, safety, security and efficiency of air transportation operations while at the same time keeping complexity and cost of on-board networks and equipment within a sustainable level.

This is indeed the truly integrated modular approach for a global aeronautical network and communication architecture in the focus of SANDRA.

The SANDRA design of a seamless network

There is a need for a new approach in order to achieve the aforementioned broader level of integration. As spotlighted above, there are many attempts to reach the goal of a future worldwide seamless networking in aeronautical communications within the next decades. The European project SANDRA supports the achievement of this objective in:

- defining, integrating, and validating a reference communications architecture directly related to the service-oriented avionics architecture envisioned by the Future Communications Study;

- establishing the feasibility of integration the SESAR concepts into the overall communications system of future airliners;

- taking into account the integration of all communications domains (ATS, AOC, AAC, APC) to pursue economic efficiency and robustness in critical situations;

- integration of the existing and future network technologies including the interfaces to integrated radio technologies (VHF, AeroMACS, L-band, and Ku-band); and

- speeding up research and standardization.

For reaching the above goals the SANDRA integrated network concept has IPv6 as final unification point as indicated by ICAO (International Civil Aviation Organization) for its future IP-based aeronautical telecommunications network (ATN).

3. Main S&T results/foregrounds

a Requirements and global system architecture

Starting from the system hypothesis, current state of the art and operational concepts as input to the future system architecture, the goal of this activity was to provide together with the system requirements (WP2.1) and operational scenarios (WP2.2) the relevant system inputs to other SANDRA WP activities, in particular aspects related to the networking aspects. The focus has been

put on aspects related to mission and services handled by the SANDRA system. They are mainly user and operation oriented.

Hypothesis and state of the art on current and future services and data link technologies, mapping between services, networking solutions and data link technologies, and operational hypothesis for the multilink support within the SANDRA system, including the system requirements and regulatory constraints applicable to the future SANDRA system have been analyzed in details.

Based on the outcome of the multiple subprojects of the SANDRA action, the SANDRA system architecture was derived based on the protocols and network architecture defined in SP3. This system architecture was further updated based on the results of simulations performed in SP3 and possible changes to the network architecture.

The SANDRA system relies on different types of data links:

- Satellite: handling A/G communications via satellite (based on at least safety and operational consideration, the satellite system used for ATS/AOC services can be different from the one used for AAC/APC services)

- Terrestrial: handling A/G communications via a direct radio link between aircraft and ground and A/A communications (at least point-to-point communications)

- Airport: handling A/G communications via a direct radio link between aircraft and airport infrastructure (the general use is for aircraft on ground).

These data links are used by the various considered aircrafts in their different phases of flights. A second part of the analysis has further defined the different usage scenarios for each of the available data links for multiple considered user profiles. Example of these elements are provided on Figure 3 and Table 1 below.
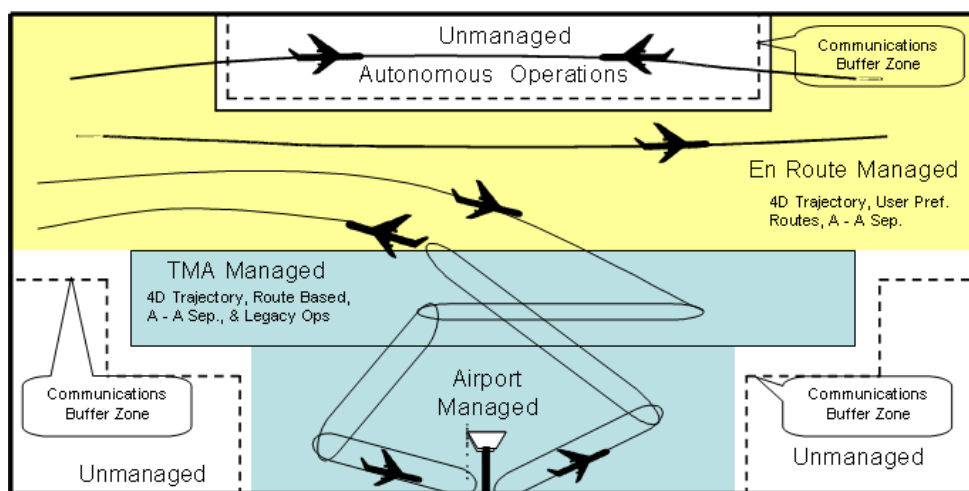

**Figure 3: Example Environment Airspace Organisation**

ATS functions	Departure gate Tx	Rx	Departure Taxi Tx	Rx	Take Off Tx	Rx	Climb Tx	Rx	Cruise Tx	Rx	Descent Tx	Rx	Approach Tx	Rx	Landing Tx	Rx	Arrival Taxi Tx	Rx	Arrival gate Tx	Rx
Procedure clearances	2	2					2	2	2	2	2	2	2	2						
D-TAXI			1	1													1	1		
En route CPDLC							1	1	1	1	1	1	1	1						
4D-TRAD / ADS-C			2	2	2	2	2	2	2	2	2	2	2	2	2	2				
4D ASAS							1	1	1	1	1	1	1	1						
Flight Plan Update & Integrity	2	2					2	2	2	2	2	2	2	2						
FIS	2	2	2	2			2	2	2	2	2	2	1	1			2	2		
Digital voice	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
AAC functions	2	2	2	2			3	3	3	3	3	3	3	3			3	3	3	3
FOC functions	2	2	2	2			2	2	2	2	2	2	2	2			3	3	2	2
APC functions																				
High Speed Internet	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Phone/Fax	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
TV broadcast		4		4		4		4		4		4		4		4		4		4

(red)	Tx is a triggered by system (periodic or not) transparent to the crew
(red)	Rx can occur at any time / is active all the time
(cyan)	Tx is active only upon aircraft user action
(cyan)	Rx occurs only in response to a Tx within appropriate timeframe
(yellow)	Inhibited use
1	Tx/Rx can not be missed/delayed/interrupted
2	Tx/Rx can not be delayed by more than seconds (<10)
3	Tx/Rx can not be delayed by more than minutes (<5)
4	Tx/Rx can be delayed and/or interrupted in order to free bandwidth/resources for higher priority services
Blank cell :	N/A or no operational use

Table 1: Example link usage apportionment for Business Jet scenario

The same approach has been follow for the commercial airliner scenario as well as the UAS environment presented on Figure 4 below.

Figure 4: UAS data links
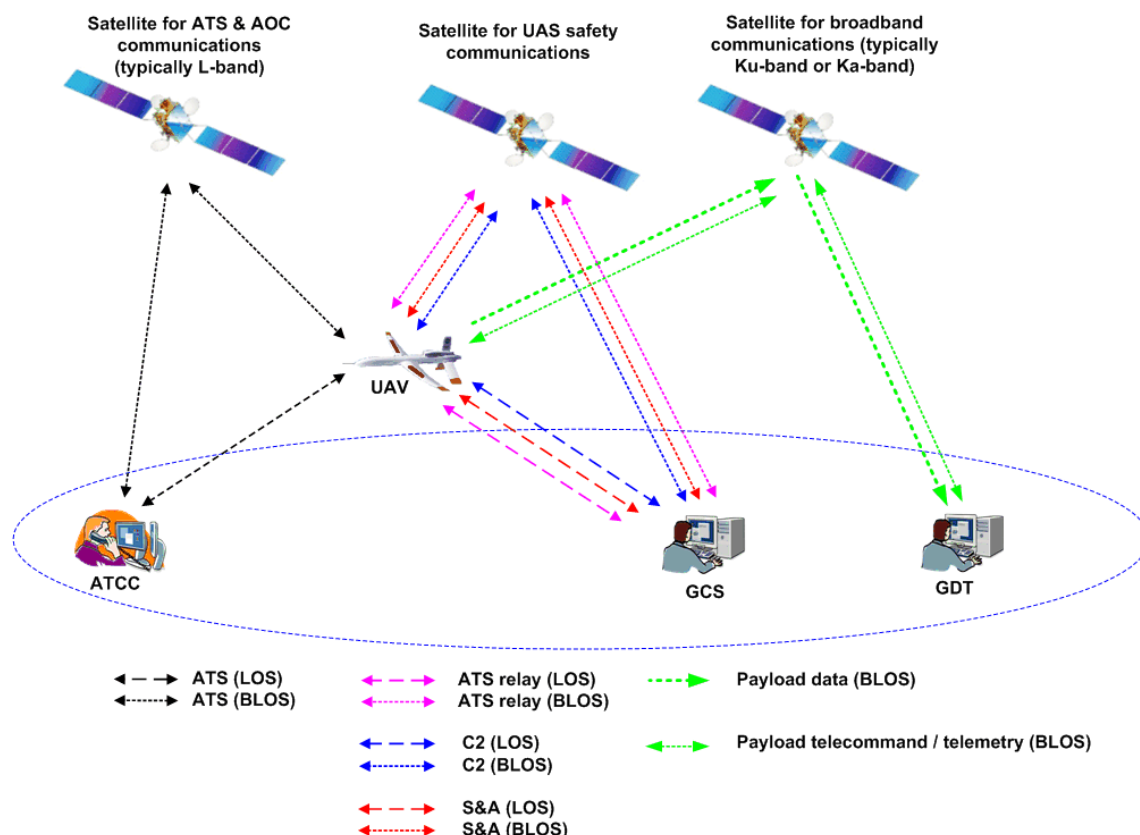
Based on this analysis, the system architecture has been consolidated taking into account the outcome of the activities performed in the other subprojects of SANDRA. Multiple scenarios for the transition between the current systems and future architectures integrating the SANDRA concept have been studied. The impact of the SANDRA system integration both onboard the aircraft but also in terms of ground infrastructure and role players has been analysed.

Figure 5 illustrates the overall system architecture identifying all the main components involved in providing the services to the users.

Onboard, the users of the SANDRA system are, all the classical ATS and AOC applications but also the SWIM airborne middleware currently under definition and potentially all "connected equipment" such as non-critical cockpit equipment (e.g. EFB, ...) and passenger equipment (e.g. laptops, PDA, ...).

On the ground side, the SANDRA system provides services to either national or regional ANSPs but also the Airlines and classical Internet Service Providers allowing them to provide services to either their onboard counterpart or directly to passengers.
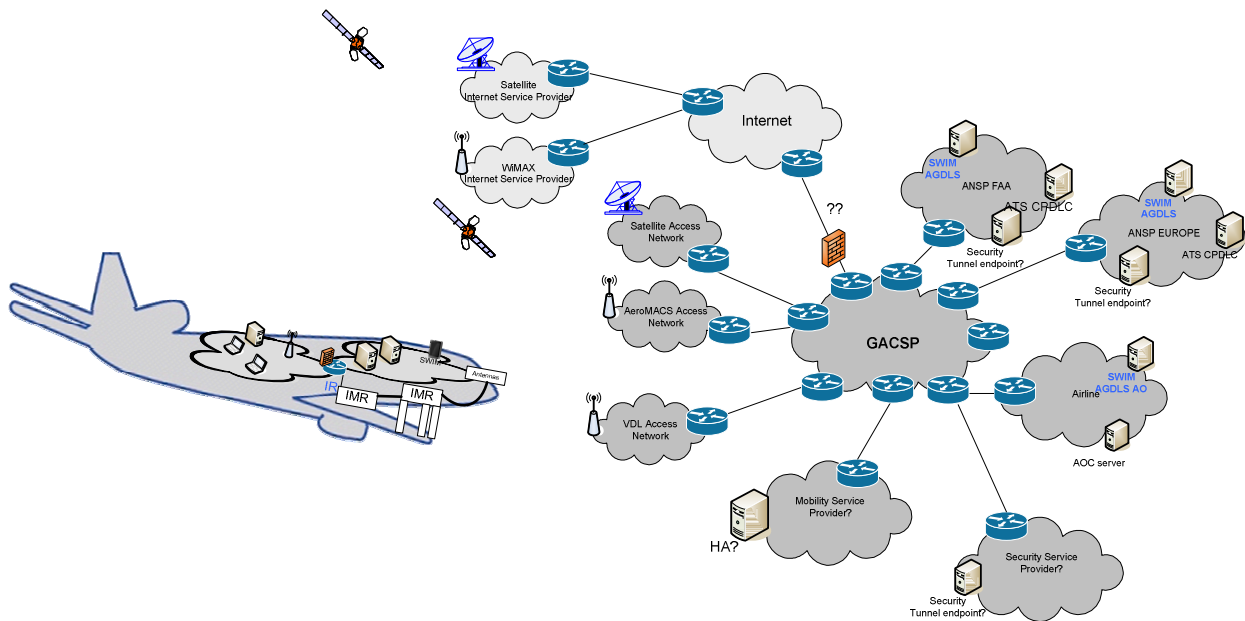
Figure 5: Overall System Architecture Overview

b Seamless Networking

There is a need for a new approach in order to achieve the aforementioned broader level of integration for the required increase of capacity, safety, security, and efficiency of air transportation operations which keeps at the same time the complexity and cost of on-board networks and equipment within a sustainable level. As spotlighted above, there are many attempts to reach the goal of a future worldwide seamless networking in aeronautical communications within the next decades. The SANDRA project supports the achievement of this objective in:

- Defining, integrating, and validating a reference communications architecture directly related to the service oriented avionics architecture envisioned by the Future Communications Study;

- Establishing the feasibility of integration the SESAR concepts into the overall communications system of future airliner;

- Taking into account the integration of all communications domains (ATS, AOC/AAC, APC) to pursue economic efficiency and robustness in critical situations;

- Integration of the existing and future network technologies including the interfaces to integrated radio technologies (VHF, AeroMACS, L-band, and Ku-band);

- Speeding up research and standardization.

For these goals the SANDRA integrated network concept with IPv6 as final unification point (target 2025 and beyond) is developed. The overall SANDRA network structure is shown in Figure 1.

The integration of different service domains with very heterogeneous requirements through a cost-effective and flexible avionic architecture is thus one of the main challenges addressed by SANDRA. Under this perspective, the SANDRA communications system presents a key to enable

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the global provision of distributed services for common decision making based on the SWIM concept, and to meet the high market demand for broadband passenger and enhanced cabin communications services.

Network Architecture and Interoperability

Before the definition of a new network structure can start a detailed consolidation of existing and on-going network and system requirements is needed. The definition of a functional architecture for such a complex system aims at integrating the major network functions and the message exchanges between main functions. Hence, a description of the data exchange for the data plane, the control plane, and the management plane is needed. Furthermore, a specification of the characteristics depending on the type of services is required in the data plane, e.g., quality-of-service (QoS) management, link or traffic profile characteristics.
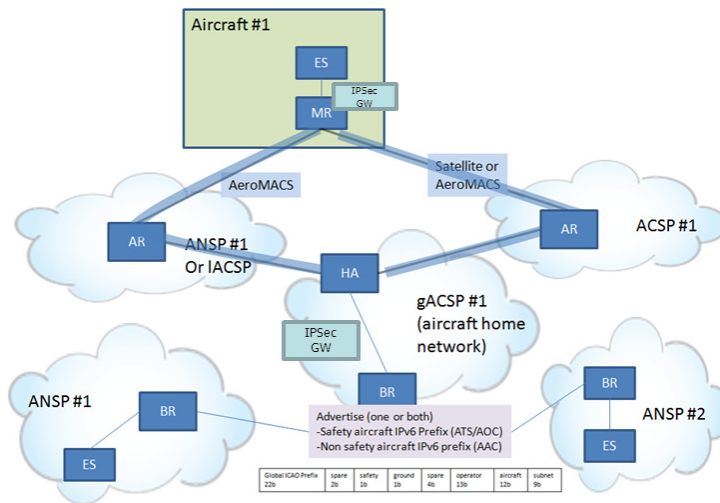

Figure 6: Illustration of the basic communication architecture model

Middleware and Service Integration

Based on SESAR's vision, future airborne systems will interoperate with ground systems by using a SWIM airborne side middleware instance. The possibility of an extension of SWIM capabilities towards the integration of different domains is investigated in SANDRA. In addition, SWIM is very bandwidth demanding which can be hardly offered by current data links for airborne/ground service. Therefore, SANDRA adds a new airborne part, called SANDRA Airborne Middleware (SAM), to the SWIM concept which takes into account legacy data links and future data links. Main task of SAM is the translation of SWIM information to a compressed information-complete format which can be fed through the existing and future data links. SAM is compliant with the overall SWIM concept, and therefore, an air-ground service is enabled to the SWIM ground middleware.

Global Security Concept

Future safety related communication as in aeronautics will require a security concept handling threats and attacks to the system. The SANDRA security concept removes the segregation between different services (ATC, AOC, AAC, APC), as existing today. This is in line with SESAR's AOC Study stating the old segregation of ATC / AOC and AAC and APC is fading. The security concept is

approached by the view on two subsystems: the ground and the airborne system. Furthermore, assets identification, threat scenarios, risk estimation, and risk treatment were identified and developed. Within the SANDRA project network-based security issues were investigated on Layer 3 with the focus on IPv6.

Network Design

Since IPv6 is the unification point in the SANDRA network, there is the need of design and adaptation of the network infrastructure to an aeronautical internet. One focus within this task is the handling of network management and also of resource and QoS management. Additionally, effort is spent for the development of new and efficient handover and mobility management algorithms and concepts, respectively. Also an IPv6 based naming and addressing architecture is provided. In the following a selection of results are highlighted.

For the SANDRA Terminal, the lower layer (link and physical layer) functions are provided by an on-board IMR consisting of heterogeneous radio access technologies. The upper layer (layer 3 and above) functions are managed by an IR. The interface between these two entities is realized by the use of the IEEE 802.21 MIH (media-independent handover) framework and an extension of the ETSI BSM (broadband satellite multimedia) SI-SAP concept. Thus, the combined usage of both standards considers the separation of technology-independent upper layers from technology-dependent lower layers to enable interoperability among heterogeneous networks.
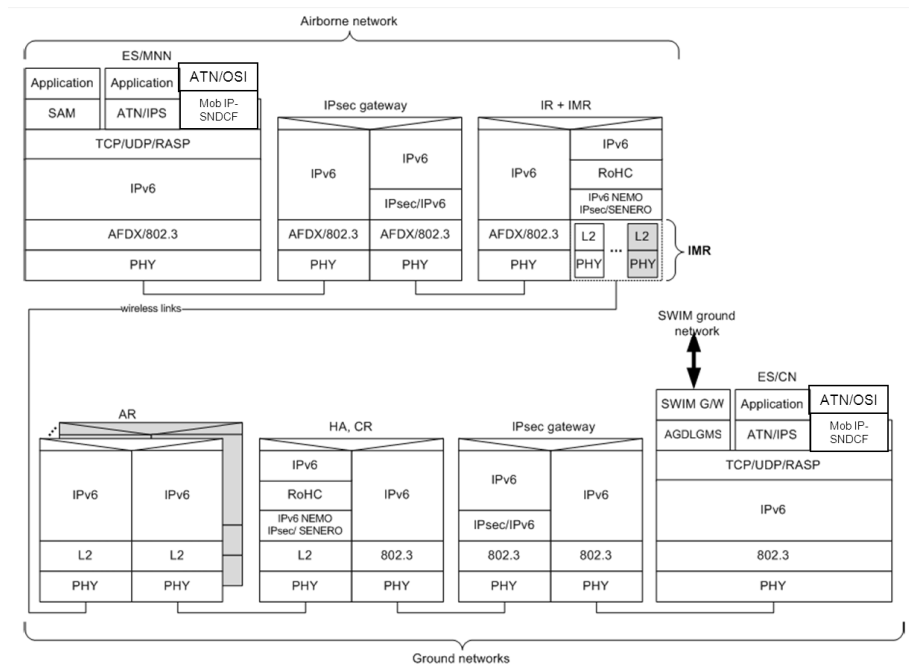

Figure 7: SANDRA IP network protocol stack

Work on IPv6 network mobility (NEMO) protocol is done due to the high degree of mobility on a global scale and the heterogeneous network environment consisting of short-range and long-range terrestrial as well as satellite access technologies. The mobility concept is based on a mobile router, located in the aircraft, performing handovers between access routers in the different access networks and geographical areas, e.g. on the American or the European continent.

In terms of naming and addressing the main outcomes are: (a) one or multiple IPv6 prefixes can be assigned to one aircraft; (b) the same system can support multiple IPv6 prefixes; and (c) it is envisioned to have a provider dependent prefix for the Pax System and ICAO standard prefixes for avionics and aircraft systems.

Additional novelties towards the network design as findings of SANDRA are: (a) development of a new security and signalling mechanism called Secure NEMO Route Optimization (SeNERO) protocol to Mobile NEMO tunnels as a route optimization solution; (b) introduction of Robust Header Compression (RoHC) techniques; (c) implementation of a new transport protocol called Reliable Aeronautical Services Protocol (RASP) providing a reliable data transport for message-based applications such as ATM services; and (d) proposing XCP (eXplicit Congestion Protocol) for avoiding congestion and optimizing link usage.

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.
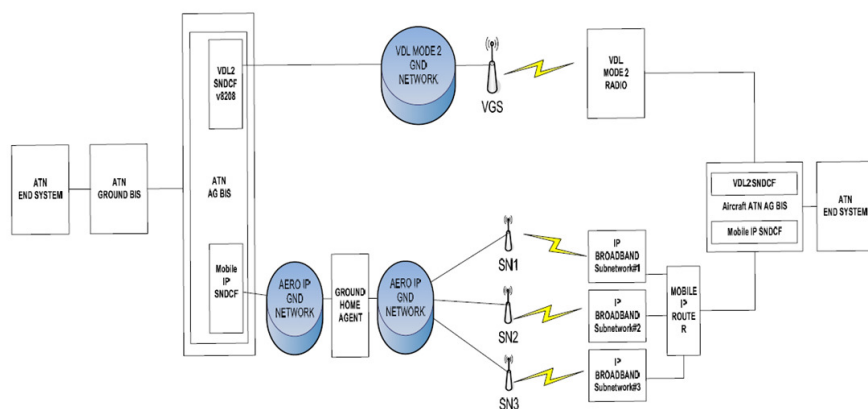

Figure 8: SANDRA Mobile IP-SNDCF architecture

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. This allowed demonstrating end-to-end ATN/OSI communications over VDL2 and SANDRA mobile IP implementation over BGAN and AeroMACS.

An Aeronautical Mobile ad hoc Network (MANET) Approach

The aeronautical MANET is envisioned to be a large scale multi-hop wireless mesh network of commercial passenger aircraft connected via long range highly directional air-to-air radio links.

Principals of MANET technologies will be applied to aeronautics, as exemplarily shown over the North Atlantic in Figure 4. A geographic load sharing strategy fully exploiting the air-to-ground capacity is proposed. Traffic is spread among a set of next-hop candidates based on queue dynamics. In addition congestion-aware handover strategies are applied for load balancing the Internet gateways.

Validation, Simulation, Implementation, and Testing

A large effort is spent in the validation and testing of the SANDRA integrated airborne network design. Capacity limits and overall system performance on future air traffic scenarios, services, and applications are assessed. This gives input to the development of a prototype implementation and its testing. Large scale simulations of the IPS network design are investigated. The lab trial architecture and their implementation reflect the overall SANDRA networking architecture. Several regional areas are embedded and all the data links are represented and connected to the airborne network. Furthermore, different applications serve all required services. In the end, the overall SANDRA concept was validated and demonstrated within a test bed and during flight trials, in June 2013 by SP7.
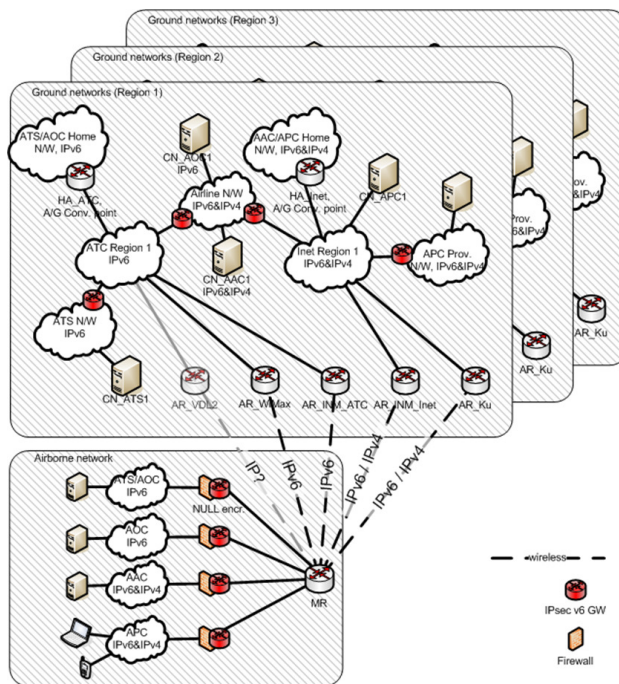

Figure 9: SANDRA network architecture for simulation and testing

c Integrated Modular Radio

The SANDRA programme was constructed to test and develop various technologies, architectures, and ideas for an eventual product called Integrated Modular Radio that Thales UK and the University of Bradford had developed in earlier studies predating SANDRA. The architectures and particularly the demonstrator were configured to facilitate these studies and were never considered to be indicative of a final product. This is an important point which has been lost on some observers of SANDRA. The key document in understanding these issues is the SANDRA IMR Design Study Report (D4.1.1.2) which considered how an Integrated Modular Radio (IMR) System might be

designed. It examined the general requirements and candidate architectures for such a system, and examined them against some of the issues which affect the design choices for the equipment. A comparison was made between the architectures. Finally two software architecture approaches were evaluated. These were compared and contrasted and the certifiability of each was evaluated.

An IMR system is intended to be capable of providing the complete communications infrastructure for an aircraft. The systems which are candidates for the inclusion of IMR modules include radio and satellite communications, TCAS, ILS and many others.

Radio functionality splits into three main components:

- "The Front End" which includes antennae, HPA and DLNA;

- "Transceiver Functionality" which includes band specific RF circuits, ADC and DAC;

- "Processing Functionality" which includes DSP, channel coding protocol stack and application.
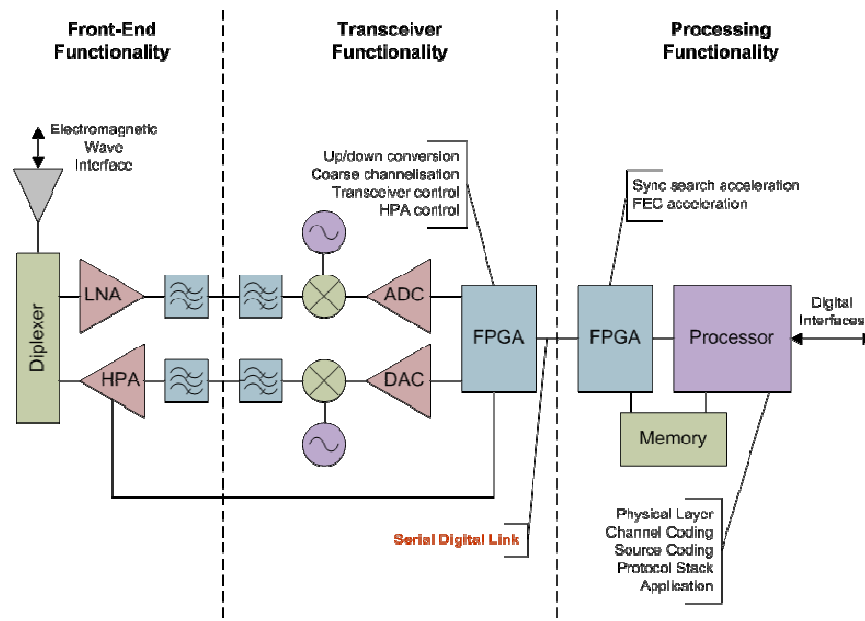

Figure 10: Partitioning of Radio Functionality

The ability to combine functionality for the different systems in "The Front End" and "Transceiver Functionality" is severely limited by issues such as dynamic range and co-site problems for example. However, a large percentage of modern radio functionality is implemented in software and by using a common processing platform development, testing and maintenance costs may be reduced. Two main architectures have been considered to address the IMR concept. A Centralised Architecture where the processing functionality is centralised in dedicated processing modules and a distributed architecture where a common processing module design and implementation is used for each of the radio modules.
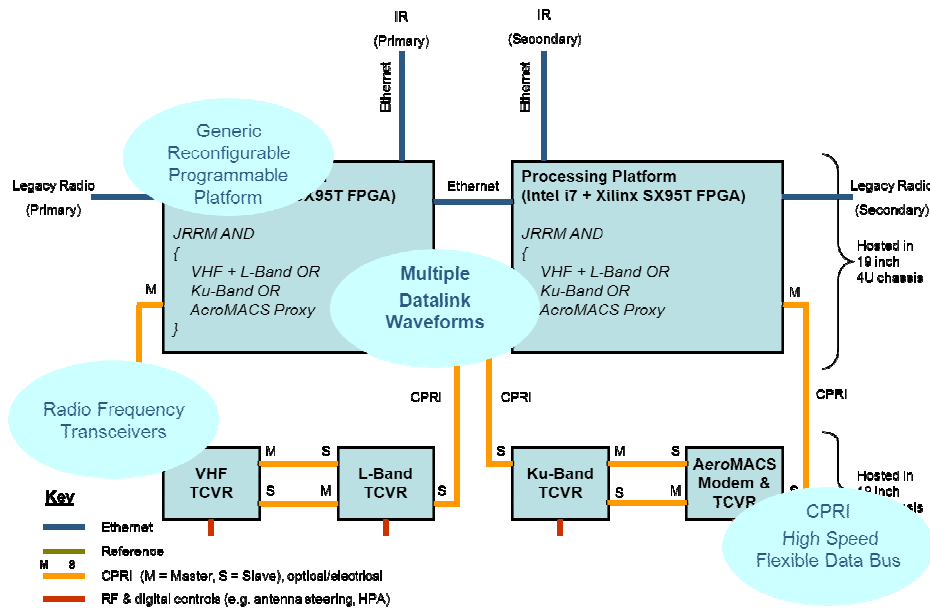
Figure 11: Integrated Modular Radio SANDRA prototype, exploring IMR principles

IMR as a concept raises a number of issues. With current aviation communications systems most are isolated from one another and have little in the way of security mechanisms. However, with an integrated system which contains a large amount of digital signalling this is no longer the case and security is an issue which must be addressed. Security poses a different set of problems to safety although superficially the certification processes are similar. The IMR Design Study Report conducted reviews of the different security initiatives being carried out within the aviation community, which are on-going and, as yet, without a consensus of approach.

Another issue to be considered with IMR is support for Seamless Networking, including handling of asymmetric links. While the majority of this is handled at the network level, it has an impact on the IMR radio as a consistent interface has to be provided by all the links supporting Seamless Networking. In a fully integrated communications system, the IMR would in all probability include within it the network routing and resource management functions. However, as an expedient way of partitioning the areas of responsibility and work in the SANDRA programme, the Integrated Router was partitioned away from the IMR. The Resource Management function provides the interface between these two areas of functionality and its function is split between the two areas. This was a purely pragmatic decision but which affects the way in which many of the higher level functions are considered both by SP4 and SP3. An unintended consequence of this was that the term IMR came to mean only the SDR part of the overall communications system, whereas, previously, IMR had included all of the routing and radio management functionality. This has led to the adoption of a new term IMC (Integrated Modular Communications) to mean the entire system.

To provide a whole communications system by means of an IMR equipment will require the issues such as resource and redundancy management to be addressed as well as re-configuration of the system. Finally the largest issue is likely to be certification of such a system as the combined system is likely to be rated at a higher DAL level than the current individual radio equipments and hence modular or component certification mechanisms will be required.

In order to evaluate the candidate IMR architectures, the above issues were used as points of comparison. The findings of this comparison showed that the decision as to which type of architecture is best is not clear cut, but a choice had to be made, and the SANDRA IMR architecture as implemented in the proof of concept demonstrator ended up being a centralised architecture. Based on the SANDRA experience, it can be concluded that the centralised architecture worked well, so it recommends itself as the way forward. The possibility of running multiple waveforms concurrently on one processing platform was demonstrated, as was the provision of redundancy and failure management.
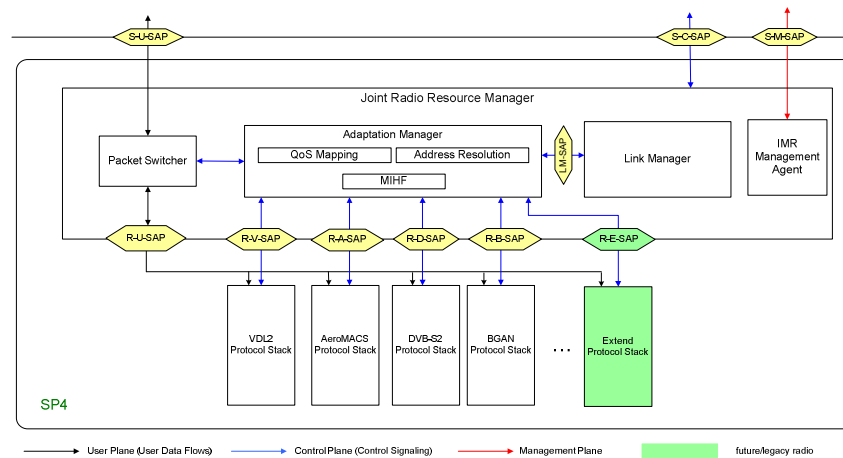

Figure 12: IMR Joint Radio Resource Manager architecture

Another key area of study was the digital bus that connects the transceivers to the baseband processors. Here again SANDRA built on previous work. CPRI proved to be a good choice, and the other standards that were considered (PCIe and SRIO) were shown to have been not as suitable. The chaining of transceivers and the ability to reach a given transceiver via different routes (important for failure management) required the implementation of a CPRI switch.

A number of lessons were learned from the detailed implementation of the radio modules:

- Defining the software application principles early on helped partners develop applications that could be integrated together.

- The use of an operating system with a process model (QNX) allowed different applications to be run concurrently.

- The definition of interfaces with other partners also worked well and this facilitated the integration of the different applications.

- Establishing the optimum priorities of the different tasks in the L-Band stack application proved troublesome but was eventually found. Several important lesson have been learnt from this experience.

During the implementation of the Radio Resource management, the following was learnt:

- Modular designs together with sufficient and clear interfaces definitions have brought invaluable benefits to the project. The JRRM had to interface with the IR, BGAN stack, DVBS2 stack, AeroMACS Proxy, VDL2 stack, Supervisor Application, Network Management Agent and Flight Status Emulator. Clear definitions of the interfaces via common set header

files sharing made it possible to develop and debug the JRRM codes independently and remotely from all the applications developments.

- Event triggered messages handling processing is essential for JRRM. Instead of checking messages in the queue periodically, all messages were processed based on queue message arrival notification events immediately. This ensures minimum JRRM processing delay and saves the CPU processing time utilised by the JRRM. For messages requiring a long time to complete, for example, the loading of waveforms, or opening a connection, internal queues are created to buffer them and process them in separate internal queue working threads.

- Multithreading, prioritisation and use of mutex are other good practises to implement complicated message processing systems.

- Reasonable usage of the configuration files makes the JRRM more flexible and general for different test scenarios and integrations. For example, Master JRRM and Slave JRRM can use identical executable but with different behaviours; the JRRM can work with or without the presence of the Supervisor for individual tests with specific radios; the JRRM can be configured to use different network addresses, interfaces; the JRRM can be configured to allow different combination of waveforms; it can be given different time out values to suit different networking working conditions; it can be instructed to load/unload different waveforms on the same flight phase; and etc.. All the above capabilities are realised by reasonable usage of configuration flags instead of hardcoding them in the software, it also saves considerable amount of time during integration with partners since there is no need to recompile the codes, but instead make a change of the flags.

- Due to the nature of the inter-processing mechanisms of the QNX POSIX messages queues, once a queue is unlinked (deleted), the listener of the queue will not be able to receive any messages from that queue without reopening the queue. Although the owners of each queue have been clearly documented, this behaviour still creates lots of problems in the early stage of the developments. So, some careful thought about the timing and usage of the unlink command is important.

- Always pay enough attention on version managements of the source codes. This will not only save time by avoiding debugging the same errors caused by obsolete pieces of code, but also ensure an efficient development and integration environment for the whole project.

The interface between the JRRM and Supervisor worked, with the Supervisor monitoring the health of those waveforms / applications that it had launched, either autonomously or at the request of the JRRM. The Supervisor correctly restarted waveforms that had failed but were still required by the JRRM, and removed those waveforms no longer in use.

A disappointment was the time it took to launch the waveforms; which resulted in delays between starting a physical layer and the waveform/stack being launched. This was, in part, necessitated by the need to ensure that the queues had been created in time. This has implications for handover in situations where a waveform crashes, or when an CPU crashes and the IMR/IR has to handover. Seamless transfers when all waveforms are running is achieved by the JRRM starting the waveform intended to take an existing 'stream' being started sufficiently ahead of ceasing to use the waveform currently handling that stream.

Finally, the report Avionics Integration (D4.1.2.1) detailed the investigation of how an IMR might be integrated into the rest of the avionics. Its primary conclusion was that the software defined radio elements of the IMR were definitely **not** suitable for integration with the IMA, but the router elements of the IMR, developed for programme management convenience in SP3, and known as the

"Integrated Router", could be, and probably should be integrated into the IMA. Indeed a partial integration of this type of functionality has already taken place in the latest Boeing 787 and Airbus 350 aircraft. However these aircraft do not have the equivalent of the JRRM functionality. The JRRM requires some close coupling between the IMR and the routers, and it was concluded by the JRRM team (University of Bradford) that the IR should be integrated into the IMR instead, as was envisaged in the original IMR concept that pre-dated SANDRA. Additionally, there are some other considerations relating to the switch network topology and reconfiguration mechanisms in the event of failure (whilst maintaining security segregation) which could significantly influence the integration question and have not been investigated in any depth in the SANDRA programme or elsewhere. Further study is needed before a firm conclusion could be made of the benefits of integrating the IR with the IMA.

d Integrated Antenna System

The objective of SANDRA SP5 was the development of an integrated Ku-band/L-band phased array antenna. A key requirement for future aeronautical communications systems is the provision of broadband connectivity within aircraft cabins at an affordable price. One of the key enablers is an electronically steered Ku-band phased array. Since most of the cabin data is highly asymmetrical, with the inbound traffic being about 5 times higher than the outbound, only the inbound traffic requires the availability of a broadband Ku-band antenna (receive mode only). A further benefit of a receive only system is that the beam width restriction to avoid inadvertent irradiation of other satellites can be reduced; this is a particularly useful amelioration as it means that the phased array can be used (maybe, at slightly reduced data rates) at low elevation angles, where the beam tends to flatten out. Obviously, the transmit part of the data exchange must use a different bearer. For this it was proposed to use an Inmarsat SBB link. This L-band link will have both receive and transmit capability, in fact, and will use the transmit capability also to support the high bandwidth Ku band receive system. Thus the integrated antenna will be L-band receive and transmit capable as well as Ku-band receive capable.
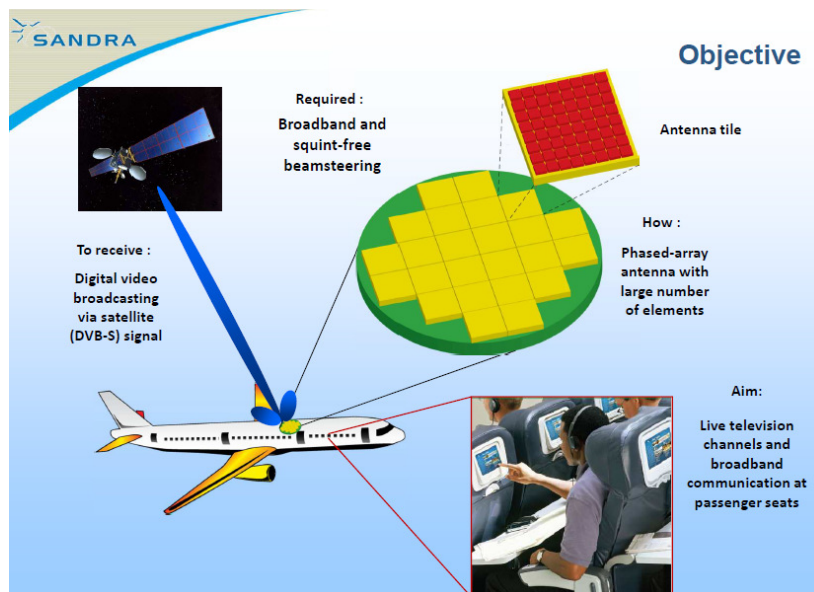

Figure 13: SANDRA integrated sitcom antenna system

SP5 started with a review of the requirements for L-band and Ku-band SATCOM antennas. These requirements encompassed System and maintenance requirements, Environmental conditions, General Electrical requirements, Electromagnetic Compatibility requirements, Certification requirements, RF requirements and Installation requirements.

Requirements were derived for a final production antenna and for a prototype antenna to be built during the project. These requirements have been reported in:

- D5.1 Intermediate Requirements Report
- D5.6.2 Final Requirements Report

The main RF requirements were the bandwidth of at least 2 GHz and the beamwidth of 2°. The requirement for broadband reception was the main driver for the selected beam-forming architecture with True Time Delays (TTDs).
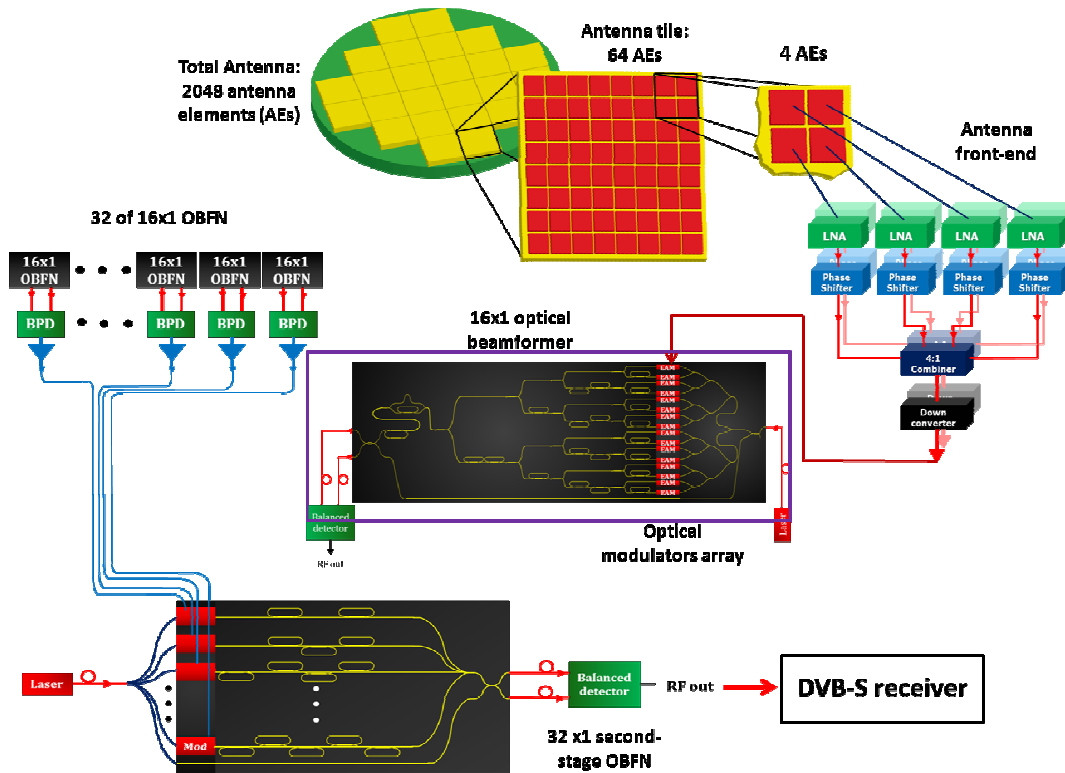
Figure 14: Ku-band RX only system architecture

Dedicated requirements were derived for the optical beamforming system and the optical beamforming chip. Optical Ring Resonators (ORR) are used to perform the True Time Delay (TTD) function. Because of these TTDs, instead of phase shifters, the beamformer has broadband capabilities. The requirements for the optical beamforming system address the laser, the optical modulator, the Optical Beamforming Network (OBFN) and the photo-detector. The requirements for the optical beamforming chip address the ring resonators, combiners, phase shifters and filters inside the chip. The requirements for the optical beamforming have been reported in:

- D5.4.1.1 OBFS Requirements Report
- D5.4.1.2 OBFC Requirements Report

In D5.4.3 (Architectural design of MMIC sub-array beamforming) a comparison was made between the classical MMIC beamforming system and a hybrid RF/Optical beamforming system. The hybrid beamforming system offers a larger bandwidth.

Based on the requirements derived for the prototype antenna, the architecture of the antenna systems was established. The total K_u-band antenna system consists of an antenna front-end and a beam forming network. The antenna system is connected to a DVB-S2 receiver. A beam forming network with tuneable True Time Delays (TTD) is used to guarantee broadband reception (2 GHz bandwidth). The antenna elements used are stacked patch antennas which also have the required bandwidth of 2 GHz.

To obtain the required gain of about 37 dB and the beamwidth in the order of 2°, the complete antenna consists of a phased array antenna with 24 to 32 antenna tiles. Each antenna tile consists of 8x8 antenna elements. The antenna system uses a hybrid beamforming system in which initial steering for sub-arrays (2x2 antenna elements) is carried out in the RF domain and the overall beamforming (16 channels per antenna tile) is performed in the optical domain. The architecture of the antenna system was reported in

- D5.2 Report for overall architecture of antenna
- D5.6.3 Final report overall architecture

During the first year of the project it was decided that the Ku-band antenna would not be part of the flight tests at the end of the project. Instead the antenna would be tested in a laboratory environment (antenna test range). In addition it was decided that a detailed design would be made for the integrated Ku-band/L-band antenna but that the demonstrator would only consist of a Ku-band receive antenna because of expected isolation problems.

The future Ku-band antenna system will use a tracking system that will steer the beam of the antenna to the geostationary satellite, based on the satellite position and the aircraft position and attitude. Probably two antennas (one on each side of the aircraft fuselage) will be used to be able to operate the system also at high latitudes (e.g. during transatlantic flights). Earlier studies have shown that in the case of two antennas, the scan angle of each antenna can be limited to 45 degrees. A study was made of the required tracking system and of the accuracy of the aircraft position and attitude. The results of this study were reported in:

- D5.4.10 Report on interface between aircraft position/attitude and antenna system

Once the overall architecture was established, then the design of the components of the antenna system started.

The Ku-band antenna front-end consists of an array of antenna elements with stacked patches. The patches have been designed to have a good impedance matching over the whole Ku receive band. In addition the antenna elements were optimised with respect to isolation between the two polarisations and with respect to isolation between antenna elements (to prevent mutual coupling). The design of the antenna elements was reported in

- D5.3.1 Report for detailed design of antenna

- D5.3.3 Final report for detailed design of antenna

In the D5.3.3 also the design of the integrated L-band antenna is discussed. Two designs were presented that could be integrated with the Ku-band antenna. The main problem is the isolation between L-band and Ku-band. This currently prevents an L-band High Power Amplifier and a Ku-band Low Noise Amplifier to share the same antenna aperture.

The design of the RF front-end was quite challenging. Because all the RF components and the IF, LO and DC connectors had to fit within the footprint of an antenna tile, the lay-out of the RF front-end had become very compact. In addition a high gain had to be realised to amplify the weak signal of the satellite received by a single antenna element and feed it to the optical modulator. In the RF front-end a core chip is used for each antenna element. The core chip houses a phase shifter and a Low Noise Amplifier (LNA). The phase shifter performs the beamforming for the sub-arrays of 2x2 antenna elements. The output of the 4 antenna elements is then combined and fed to an additional Ku-band amplifier. Subsequently a mixer and image reject filter are used to down-convert the signal to L-band. Final, an L-band amplifier is used to boost the signal before it is routed to the optical modulator. The design of the RF front-end has been reported in:

- D5.3.2 Report for design of RF front-end

The architecture of the optical beamforming system was described in

- D5.4.2 Architectural design of optical beamforming network with optical modulators

The architecture describes the optical beamforming system including the laser, the optical modulator, the Optical Beamforming Network (OBFN) and the photo-detector. Also the architecture for the ring resonators, combiners, phase shifters and filters inside the OBFN chip is addressed. Based on the architecture for the optical beamforming system a detailed design of the chip was made:

- R5.4.5.1 Chip design (Report) and lithographic mask (C)
- D5.4.5.2 Optical Beam Forming Chip design (Report) and lithographic mask (C)
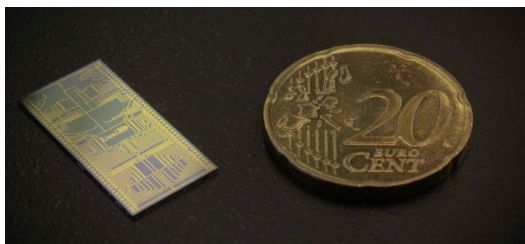

Figure 15: Optical Beam Forming Network chip

Also for the control system of the OBFN chip a detailed design was made:

- D5.4.4 Report on OBFN control system

Subsequently, prototypes of the chip and the control system were manufactured. The chip was manufactured with TriPleX technology, a CMOS compatible technology. The following hardware was delivered for further measurements:

- H5.4.5.2 Chip prototype fabrication
- H5.4.5.3 Chip prototype fabrication
- H5.4.4 Electronic OBFN control system

The measurements on the OBFN chip proofed the capability of Optical Ring Resonators to perform broadband beamforming. The True Time Delay functionality was shown to work over the whole 2 GHz bandwidth. These measurements have been reported in

- D5.4.6.1 Measurement report
- D5.4.6.2 Measurement report update

Selected OBFN chips were packaged for further integration:

- H5.4.8 Packaged OBFN chip.
- H5.4.9 Functional OBFN system module

In parallel also the development of the optical modulator was started. The selected type of modulator was an Electro Absorption Modulator. Special attention was paid to RF interfacing and impedance matching. The development of the modulator and the performance measurements on the modulator were reported in

- D5.4.7.1 Optical modulator development report
- D5.4.7.2 Optical modulator development report update

The measurements on the optical modulator showed the required bandwidth of at least 2 GHz. The sensitivity of the modulator seemed to be low. After the measurements the modulator was packaged for further integration with the OBFN:

- H5.4.7.0 RF packaged arrayed modulator chip.

Subsequently the integration of the optical modulator with the optical beamforming network was carried out and the performance of the optical beamformer system was measured. These measurements have been described in

- D5.5.2 Report with RF measurements of OBFN

The measurements showed the functionality of the optical beamforming system, but due to losses in the system as a result of the integration of the modulator with the beamforming chip and due to the reduced sensitivity of the modulator, the full performance of the optical beamforming system could not be determined.

Also the antenna array and the RF front-end were manufactured and combined into one antenna front-end:

- H5.5.4 Antenna array
- H5.5.5 RF front-end

Extensive measurements were carried on the antenna front-end:

- D5.5.1 Report with RF measurements of front-end antenna

The antenna front-end operated entirely according to specifications. Beam steering could be applied up to 60° and over the whole 2 GHz bandwidth. This Ku-band antenna front-end can be used as a narrowband phased array antenna for satcom reception.

The realized performance of the Ku-band antenna system was compared with the requirements. Most of the requirements were met, except for the link gain of the optical beamforming system. The bandwidth requirements were met by the antenna front-end and by the optical beamforming system. The requirements verification was reported in

- D5.5.3 Verification report
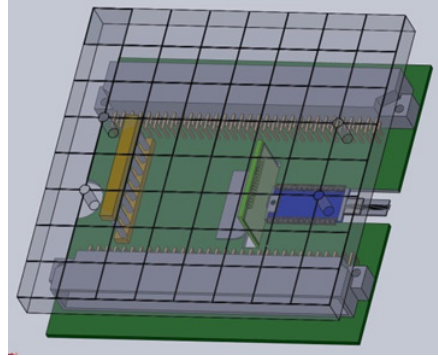
Figure 16: Ku-band RX antenna system (including OBFN and Antenna Front End)

Finally, a report was written concerning the performance of the integrated antenna. Because during the project the optical beamformer could not be integrated with the antenna front-end due to performance problems, the performance of both parts was described by means of the measurements performed on components of the antenna system. The performance of the total antenna system was predicted by simulations for a 24 tile circular antenna. The performance of the antenna has been reported in

- D5.6.1 Report with performance measurements of integrated antenna

Figure 17: *Broadband Optical Beamforming Network measurements*

This report also describes the expected performance of the Ku-band antenna installed on an aircraft. Both the installed antenna performance and RF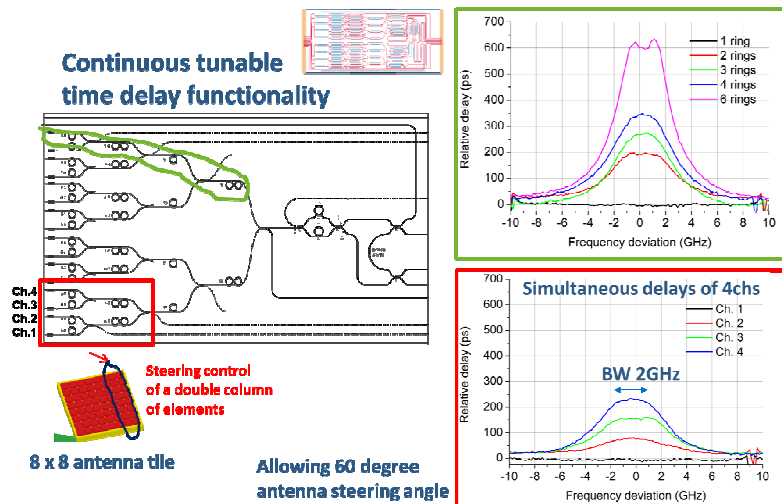 Compatibility between the Ku-band antenna and other antennas on board of the aircraft was investigated by means of electromagnetic modelling and simulation.

It can be concluded that some major steps have been made towards the design of a Ku-band receive antenna for satellite communication on aircraft. The performance of most of the components for this antenna proofed to be sufficient. Measurements have shown the feasibility of a broadband phased array receive antenna at Ku-band. The remaining work is primarily in the field of integration between the components of the antenna in order to reduce losses. Also the sensitivity of the optical modulator needs to be increased.

The research carried out in the field of optical beamforming is highly innovate and therefore also bears some risks. The chip developed in the project is a compact chip with low losses in the optical wave guides. Many publications have been written about the optical beamforming system and the optical beamforming chip. Three papers are highlighted as Breakthrough in Microwave Photonics 2010. The University of Twente is credited for the world's first integrated photonic chip discriminator for an analog photonic link. The OBFN chip is also highlighted in Nature Photonics as a technology breakthrough.

The research carried out by ACREO supported the development of an optical modulator array in addition to their existing discrete modulator technology. The RF performance of the modulators was investigated in detail.

The research carried out by LioniX in the SANDRA project focused on the further development of the TriPleX platform for Optical Beam Forming Network (OBFN) applications. Main issues there were the technology development itself and the assembly of the complete optical device. For the waveguide technology the main developments were in the further improvement of the waveguide definition and the realization of low loss spot size converters for an efficient coupling to and from the chip. In both areas large steps were made. The waveguide definition and the corresponding etch recipe was fine-tuned to realize better performance of the waveguides and a higher packaging density on chip was realized (for smaller chip footprints). Building blocks were developed in the waveguide technology to allow densely packed Microwave Photonics on chip with a proper design tool. The hybrid combination of the TriPleX OBFN and the EA modulators also required new assembly processes to be developed. Together with XiO Photonics the assembly of a hybrid combination was developed.

The multi-layer Printed Circuit Boards (PCBs) for the antenna front-end were manufactured by Cyner Substrates. The manufacturing of these multi-layer PCBs was very challenging because of the many layers of different materials, the different substrates used in each layer, the dense lay-out of the components and the incorporation of vertical transmission lines. During the project the manufacturing process was improved which led to the successful prototype of the antenna front-end. In addition flexible print technology was used to connect horizontal and vertical prints in the antenna stack.

The RF front-end design carried out by IMST showed their knowledge and capability to design complex front-ends in a compact structure. The design encompasses RF beamsteering technology

and high link gain at microwave frequencies (Ku-band and L-band). Also the assembly of the front-end with many RF components and connectors showed their excellence in this field.

The research institutes NLR and EADS-IW increased their knowledge on the design of conformal array antennas for satcom on aircraft, in particular the integration of a Ku-band and L-band antenna and the integration of the Ku-band antenna with the RF front-end. Together with Alenia the knowledge was also increased in the field of aircraft antenna certification and installed antenna performance.

e Global Airport Connectivity

Worldwide Interoperability for Microwave Access (WiMAX) is a synonym for the IEEE 802.16 standard. Initially, this standard has been developed for stationary wireless communication but has later been adapted in order to support mobile wireless communication. The future aeronautical airport communication system - AeroMACS – shall be based on WiMAX, as indicated by ICAO as for Action Plan 17. In particular it shall (at least partly) adhere to the "WiMAX Forum™ Mobile System Profile Specification". It will operate in C-band within a worldwide harmonised band which ITU has dedicated to aeronautical services for safety and regularity of flights (5091-5150 MHz).

SESAR P15.2.7 and the SANDRA projects have drafted a communication system profile, which has been evaluated initially through simulations and is now being validated through field trials.

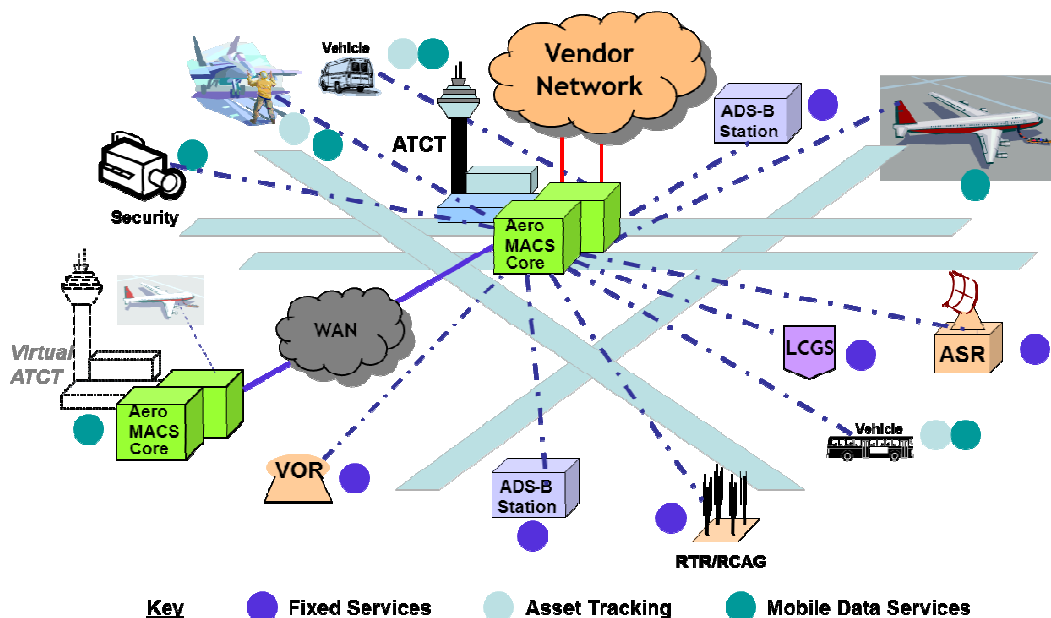**Figure 18: AeroMACS application scenario**

SANDRA focused on the design and integration of an AeroMACS network comprising Mobile and Fixed Stations based on the SESAR/SANDRA jointly defined profile based on IEEE 802.16e (WiMAX) and using the C-band for airport surface operations. Dedicated AeroMACS trials has been done in a realistic airport environment in SP6, using the airborne AeroMACS sub-system that had

been integrated in the IMR in SP4, and the overall AeroMACS system that has been integrated in the SANDRA SP7 test-bed.

Specific objectives of SANDRA activities on AeroMACS were: demonstrate that AeroMACS could be integrated of the new IPv6 based A/G Mobile Network defined in SANDRA; that AeroMACS could interoperate with future Integrated Modular Radio architectures; that the profile defined is compatible with support of Multiple Services from different aircraft domains i.e. Air Traffic Control, Airline Operational Control, Airline Administrative Communications and Aeronautical Passenger Communications.

The work has been carried out by 5 work packages: the first two Work Packages (6.1 and 6.2) focused on the analysis of WiMAX Characteristics and Airport modeling, with the goal of identifying the features to be included in the AeroMACS System Profile. These Work Packages worked in strict coordination with the SESAR 15.2.7 Project, providing, among other information, Physical Layer Simulation Results and Airport Traffic Models needed by 15.2.7 in order to properly execute MAC and System Simulations. Subsequently, the Deployment & Integration analysis started (WP 6.3) , together with the development of prototype AeroMACS airborne and ground subsystems (WP6.4) n strong collaboration with WP4.3.3 (IMR AeroMACS module) for validation of the sub-systems in dedicated trials in a realistic airport environment (WP6.5) and for overall integration in the SANDRA test-bed in SP7. This led to the delivery of Selex BSs and MSs in both the Toulouse and Oberpfaffenhofen Airports.

Several AeroMACS Base Stations (BS) and Mobile Stations (MS) prototypes have been developed and tested in accordance with AeroMACS "profile". Airport tests have been carried out both at Oberpfaffenhofen (Munich) Toulouse Airports. AeroMACS Mobile Station underwent safety of flight tests (EMI/EMC, electrical, mechanical, fireproofness, etc.) to qualify for aircraft installation.

The Complete AeroMACS system solution consisted in a AeroMACS BS, an AeroMACS SS and COTS Access Service Network-Gateway, and all other network equipment necessary for operate the AeroMACS network and tests (DHCP server, NTP server, traffic generator/analizers, etc.)

Base Station and Mobile Station prototypes have been based on the same architecture composed by two separated shelves, one for Baseband processing, and one for RF Unit interconnected by an optical CPRI (Common Public Radio Interface), an high speed serial digital link to carry base band I/Q signal.

Figure 19: Selex ES AeroMACS Base/Mobile Station

Testing & Integration activities were performed in two different test sites and labs, each focused on different functionalities:

- ✓ Genoa Labs: MAC layer software testing, integration and test of the networking solution (ASN-GW, Hand-over, Security features)

- ✓ Florence Labs: Radio Head Performances, Physical layer feature testing, mobility test
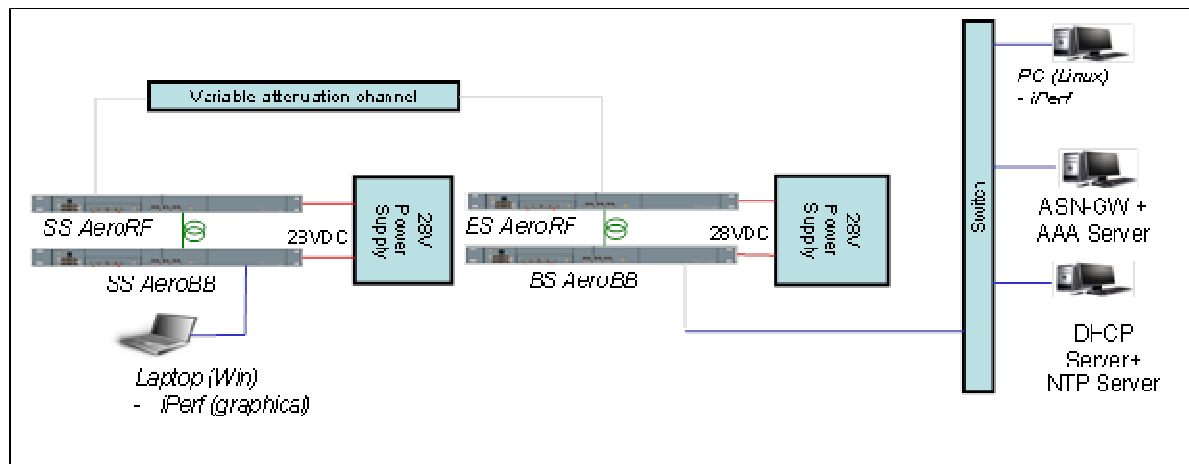
Figure 20: Selex ES Integration Test Bed

Appropriate Simulators were used in order to simulate a wide range of practical airport scenarios (different speeds/Doppler, different cases of Multipath Fading depending on the specific simulated area (RAMP, GROUND, TOWER), shadowing, etc.)

For what concerns the AeroMACS integration with IMR, this has been accomplished by means of a dedicated HW module (CPRI I/Ethernet Unit) and a SW module residing on the IMR (AeroMACS Proxy) as described in Figure 21:

- the CPRI I/Ethernet Unit has been used to interconnect the Base Band Unit, provided with an Ethernet interface, to the IMR common processing platform through high speed CPRI Bus interconnections

- the AeroMACS Proxy, residing on the IMR, provides an interface between the AeroMACS transceiver and the other software applications running on the IMR common processing platform (JRRM, Supervisor, VTManager and IMR Agent)
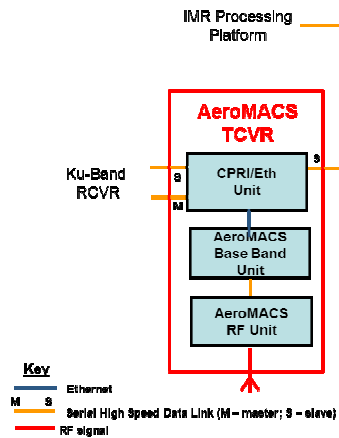
Figure 21: AeroMACS Transceiver implementation

Such architecture has been selected for validating one of the options for an IMR to interoperate with legacy radio systems.

Subsequently, as previously mentioned, Field Trials were successfully executed in Oberpfaffenhofen Airport (Car Tests and Flight Tests, under SP7) and Toulouse Airport (AeroMACS Point-to-point link tests, under SP6).
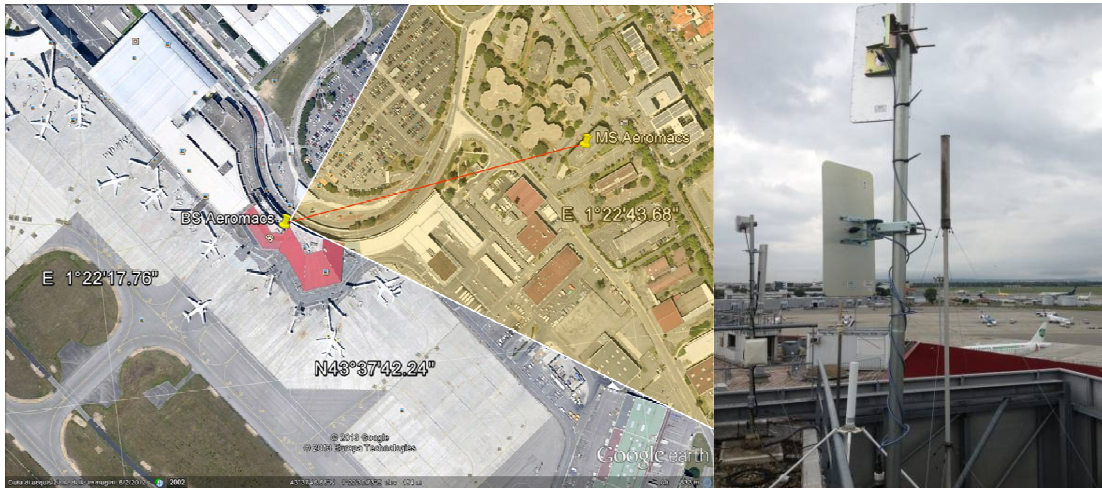
Figure 22: Toulouse Airport - BS location and antennas

Tests were successfully executed, mainly concerning Coverage, Capacity, Throughput and QoS, Application performances and stress test over a point-to-point link of approximately 400 meters.

The same set of tests were repeated, with the same successful results, on a longer link of approximately 2 Km as an initial pre-test of SESAR activities. The Network Entry Time was measured being about 10 seconds, that is a quite comfortable figure, even if it was obtained under some favorable conditions (like the absence of scanning of the whole band and authentication). Up to 4 different Service Flows with several combinations of protocols (TCP/UDP) and scheduling services (BE, nrtPS, rtPS) were successfully tested.

After SP6 has concluded its tests, the prototype network has been delivered to SP7 for SANDRA Flight Trials which have been performed in Oberpfaffenhofen. During such tests AeroMACS network has been successfully tested statically and dynamically with an MS integrated on board an A320, using several realistic aeronautical applications (see next section), although some limitations have been experienced due to line of sight blocking due to trees presence and first prototype performance limitation at 64QAM modulation (a complex modulation scheme to be used for high throughput transmission mode).

SANDRA research major results for AeroMACS can be summarised as follows:

- Studied new possible operational phases, namely: Landing, Take-Off, and Approach

- Demonstrated the possibility to implement AeroMACS radio separating base-band processing from transceiver functionality and use of high-speed digital links

- Integrated an overall AeroMACS network (Mobile Station, Base Station, Access Service Network Gateway, etc.) into the SANDRA mobile IPv6 networks

- Demonstrated support of different services with different QoS requirements: Air Traffic Services (ATS), Airline Operation Control (AOC), Airline Administrative Communications (AAC), Aeronautical Passenger Communications (APC)

- Demonstrated possibility of a Federated Radio to interoperate with Integrated Modular Radio by means of a Proxy

- Demonstrated the possibility to support legacy ATN/OSI applications on new IP based links (through Mobile IP-SNDCF)

- Demonstrated AeroMACS on a real aircraft within real airport environments

SANDRA prototypes and field trials paved the way to subsequent SESAR P9.16/ P15.2.7 Field Trials that should conclude, by the end of 2014, the verification of AeroMACS technology, bringing to the definitive System Profile Validation.

SANDRA also showed that it is possible in the short term to implement a single AeroMACS airborne terminal to provide services to both Aircraft Control Domain and Airline Information Service Domain. As a non-exhaustive example, this could be done by taking advantage of some of the SANDRA results, namely Mobile IP-SNDCF and IPSec traffic segregation.

f   Trials and Validation

The validation of the developed SANDRA concept was realized by performing lab and flight trials on the airport of Oberpfaffenhofen, close to Munich, Germany. This summary gives an overview of the outcomes of the 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, 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 system setup of the SANDRA flight trials is composed of two major segments: the airborne segment and the ground infrastructure.

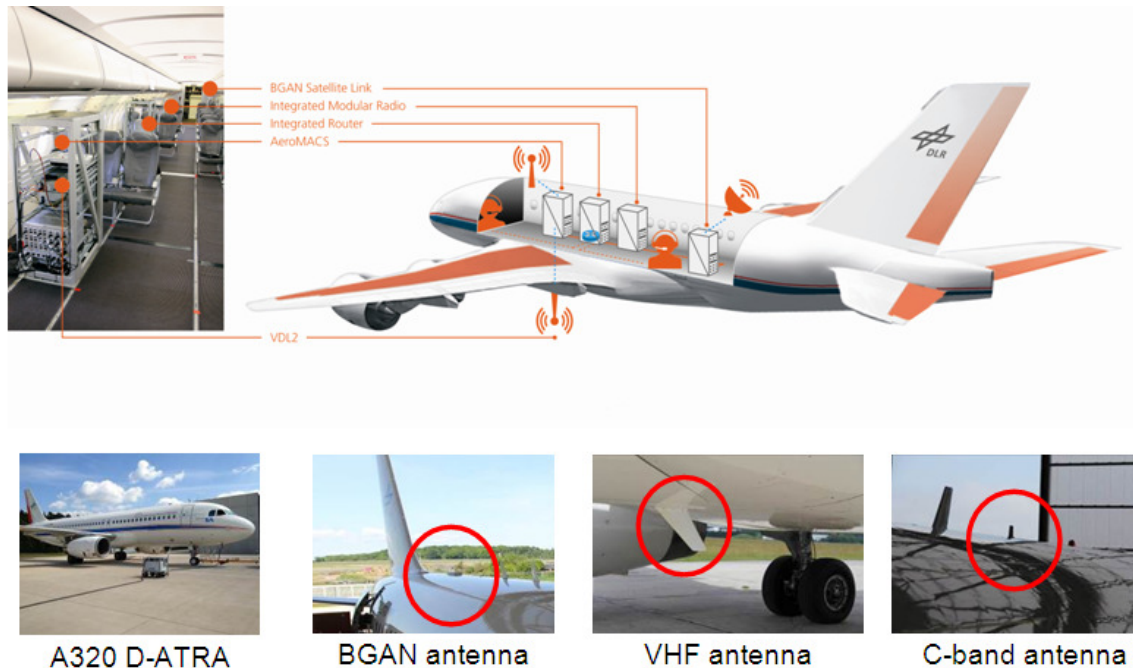The SANDRA airborne system was integrated in an Airbus A320 as displayed in Figure 23.

Figure 23: 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). 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.

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 to guarantee mobility to the airborne terminal. The IPsec integrates an IPv6-over-IPv4 transition mechanism, entitled NeXT. 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.

Description of Flight Sorties

Six sorties were made in 3 days with the D-ATRA aircraft at a rate of two flights per day (one each in the morning and afternoon). 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. Once out of the VHF coverage, the aircraft turned around to fly back over the Oberpfaffenhofen Airport and thus reentered the VHF coverage. This back-and-forth route over the airport allowed testing the seamless functionality of the SANDRA concept.

Table 2 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 2, 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.

Table 2: 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

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.

4. Potential Impact & dissemination activities

Potential Impact

Air transport industry faces a complex growth challenge, since airlines are requesting vast increases in communication capabilities for efficient operations and passenger communications. Moreover, the equipment and components lifecycles are shortening and the increasing complexity of aeronautical communication systems is becoming a major concern for airframes.

The SANDRA project will address the integration of currently separated networks in an Airborne Communication Architecture (ACA) by following a network centric approach and pursuing the convergence of ATM, AOC, APC communication technologies into one unique architecture. This system will complement the ATN infrastructure by using Internet Protocols and Integrated Modular Radio techniques technologies meeting all aeronautical application needs; integration will be investigated at the service, network, radio and antenna levels.

SANDRA will validate antenna, radio, network and information management technologies that will contribute to a significant reduction in costs for application development, network configuration, communication technologies integration. In addition, it will lead to a more efficient and comfortable aircraft environment for crew and passengers, as well as possibilities to enhance airport and aircraft logistic efficiency, in line with the goals of ACARE Vision for 2020.

The SANDRA architecture, following the IMA concept, will investigate an architecture that is significantly cheaper in equipment development, integration and maintenance costs. These features will greatly improve the market competitiveness of European manufacturers in term of sales increase and reduction of deployment, installation and maintenance cost.

The European industry today has a strong position in aeronautical and communications domains. Nevertheless, there is a strong competition from Boeing and from other US avionic companies such as Rockwell Collins and Honeywell. SANDRA will allow the European companies to reinforce their competiveness by carrying out research and validating a Network Centric Service Oriented Architecture for voice and data that will lead to a global system with the potential to satisfy the increasing request for fast adaptation, easy re-configurability and more customizability by airlines and airports.

In the first 25 years of the 21st century, European air traffic is expected to approximately double in volume and it is expected that the current aeronautical ATM communication systems will be saturated (US forecasts show similar trends). Therefore, to avoid a dramatic service quality decrease and a general passenger un-satisfaction due to lack of timeliness, the civil aviation has to count on a sufficient capacity to support this significant growth, whilst maintaining or improving current safety standards and by reducing costs to sustain international competition. This is the reason why the EU and the US launched SESAR and NextGen, two parallel massive initiatives with the respective objectives to propose a new approach to reform the ATM structure in Europe (SESAR) and to develop a Concept of Operations (CONOPS) for the next generation Air Transportation system (NextGen) that will operate in the 2020 timeframe and beyond. Such objectives will be achieved through a combination of new procedures and advances advancements in the technology deployed to manage passenger, air cargo, general aviation (GA), and air traffic operations.

SANDRA will fully validate architectures and system technologies able to initiate the transition of today's systems into a high performance network centric Service Oriented Architecture to support the Air Transport transformation, ranging from SESAR developed concepts for Air Traffic Management to Next Generation IP Networks for passenger communications and in- flight entertainment and infotainment.

SANDRA will support the high level political and socio-economic expectations of the stakeholder community, working with and providing SESAR with valuable inputs to support its decision processes.

In summary, the European Union, its citizens and industries will benefit from the SANDRA project through the future implementation of the SANDRA technologies and services capabilities, through improved efficiency, capacity and safety of their Air Transport system, reduced costs and delays and an enhanced on-board communications service offering.

Dissemination activities

First, the project produced dissemination material in form of a website, logo, to version of project's brochure, several press releases and videos. DLR, Selex ES, and Thales UK produced videos for disseminating the main outcomes of the activities in the field of SP3, SP4, SP6 and SP7. The footage of the videos is based on DLR material which could be used by all partners for free.

A key activity of SANDRA dissemination is to organise a user forum with a group of operational experts from "end user" organisations working in the technology fields targeted by SANDRA. These organizations include aircraft manufacturers, airlines, airports, Air Navigation Service Providers, suppliers of IT, radio and navigation systems and equipment, international organizations (e.g. EUROCONTROL, etc.). During the whole project duration, two user forums were organized:

- **29th of September 2011 in Rome, Italy.** The results and wrap-up of this forum can be found on the Deliverable D8.4.2.

- **14th of November 2013 in Florence, Italy**. The results and wrap-up of this forum can be found on the Deliverable D8.4.4

Overall, both SANDRA User Forums were a success by reaching all identified stakeholders.

In total 11 coordination/cooperation meetings were held with diverse SESAR projects. At the conclusion of SANDRA project, SESAR and SANDRA Radio and Data Link experts have met in Florence, hosted by Selex ES, to discuss about the future of aeronautical communications and to identify opportunities for future cooperation between the SESAR COM project and SANDRA partners. Several SESAR projects are dealing with communications, investigating at how new Air Traffic Management requirements for the Single European Sky will be supported and working on diverse aspects and focusing on Future Mobile data Link system definition (P15.2.4), Future Mobile Satellite Communication (P15.2.6), New Communication Technology at Airport (P9.16 and P15.2.7) and Flexible Communication Avionics (P9.44).

SANDRA project has been invited by WiMAX Forum (WMF) to present its AeroMACS activities and results during the WMF Aviation 2013 event in Washington D.C., USA, 10-11 September 2013. This first WMF Aviation Event drew more than 100 attendees bringing together the key players of the Aviation Community and WiMAX ecosystem to discuss opportunities for WiMAX in the Aviation Community. Attendees were treated to a full two-day program, including speakers from WiMAX

vendors, airlines, airport authorities, various government representatives from the United States, Europe and Asia, and other groups. Among the speakers also important international figures such as Nancy Graham, Director of the Air Navigation Bureau, International Civil Aviation Organization (ICAO), whose remarks made clear to participants the international support for this new market segment for WiMAX.

During the 9th of June, the already equipped Airbus A320 of DLR was used as a static display during the Open Day of DLR at their premises in Brunswick, Germany. In overall, around 4000 people were entering the aircraft having a closer look in to cabin towards the SANDRA equipment. All visitors were informed about the project by posters and project hand-outs. Figure 24and Figure 25 show the queues entering the aircraft.

Figure 24: Large interest towards the A320 and the SANDRA project at DLR's Open Days.

Figure 25: Overview of DLR's research aircraft at Brunswick during DLR's Open Days

The SANDRA Project had the great chance of showing their overall flight trial equipment at Paris Air Show 2013 at Le Bourget. DLR's research aircraft ATRA was present as a static display. Furthermore, the Project SANDRA arranges a dedicated SANDRA day, inviting all different stakeholders to have detailed insight towards the equipment and the project itself. The overall stay of the aircraft at Le Bourget was a great success. The aircraft was standing in total 5 days at Paris Air Show accessible for the public. Also the German Federal Minister of Economics and CEO of DLR were visiting the SANDRA project. Some impressions are given in the following figures.

Figure 26: Impressions of Paris Air Show 2013

In total the SANDRA flight trials were covered by 25 articles on the web in three languages.

The EU Commission announced for Sept-27, 2013 a Researchers Night in different European cities. The Project SANDRA took the chance to be also present at the Researchers Night in Pisa, Italy. At the University of Pisa, the project had the possibility to display the main concept and outcomes of the project. Approximately 500 people were visiting the SANDRA booth during this evening.

Figure 27: SANDRA booth at the European Researchers Night in Pisa, Italy, Sept-27, 2013

The overall dissemination activities were focusing on different target audiences, which could successfully reached:

- **Scientific Community** was addressed by various articles published in books, journals and conferences.

- **Technical and Industry Community** was reached by dedicated meetings and informational events such the User Forum

- **The Public** was successfully involved due to the possibilities having direct access towards the flight experiment, and therefore, understanding the immediate benefit of these kind of research projects.

Exploitation of results

SANDRA has developed and validated a new aeronautical communication architecture providing data and digital voice links between the aircraft and ground stations or service providers shared between the various applicative domains through a fully IP-based network. All links will carry IP packets, and the avionic radios' structure and functions will be developed to better handle IP packet-based communications. In addition the SANDRA radio system is modular and capable of adapt to all current and future aeronautical radio communications systems due to the definition and use of standard interfaces and waveforms.

In this section are the industrial products which could be originated, taking into account SANDRA project exploitable results and end-user trends, as reported D8.2.4 SANDRA Exploitation Plans.

Possible project exploitable results have been identified at an early stage of the project and classified in terms of TRL and exploitation timeframe, possible results have been monitored during project execution and then at the end of the project a survey with partners have been conducted in order to collect their intention to exploit project results into their product/service future offerings.

In the following table the summary of the positive responses from involved partners.

Table 3: Industrial partner's exploitation plans summary

SP	Exploitable result	Partner with exploitation plans	What specific result will be exploited?	In which product/service segment?	Could you indicate Product/Service Line?	What is the expeceted Time to Market for you product/ service?
SP2	Architecture of the Future communication infrastructures for ATM/ATS and APC	Thales Alenia Space	Ground Segment Architecture and interfaces with EATMN for the Satellite Access Networks.	Aeronautical Communication Systems	Ground Segments	2025
		SITA	architecture concept used as a baseline for defining future system architecture	Aeronautical communications	Ground segment	TBD according to regulation and business cases
	Migration Scenarios from current infrastructures to an all ATN/IPS architecture	SITA	Roadmaps & migration scenarios, associated enabling technologies	Aeronautical communications	Ground segment	TBD according to regulation and business cases
		Dassault Av.	Roadmaps & migration scenarios, associated enabling technologies	Business Jet Aircraft	Business Jet Aircraft	TBD according to regulation and infrastructure schedule

SP3	Aeronautical IPv6 network relying on NEMO (Network Mobility and Route optimization)	SITA	Overall concept and test results	Aeronautical communications	air-ground and ground segment	TBD according to regulation and business cases
		TriaGnoSys	transition of aeronautical networks to IPv6, future ATN/IPS architecture	aeronautical air and ground routers, commercial ATN/IPS test-bed	New aeronautical router and ground router line	2017/2018
	ROHC: Robust Header Compression, introduced at least at NEMO tunnel level	TriaGnoSys	efficient use of bandwidth	aeronautical air and ground routers	New aeronautical router and ground router line	2017/2018
	XCP has been proposed as the protocol allowing optimizing link usage and avoiding congestion.	Thales Alenia Space	Research on the use of XCP and improvments in router extensions.	Telecommunication Systems	Ground Segments	2025

	Integrated Router and Ground Router (Home Agent) Architecture	TriaGnoSys	soft segregation, QoS provision mechanisms, flexible use of multiple links	aeronautical air and ground routers	New aeronautical router and ground router line	2017/2018
SP3/4		Thales UK	JRRM	Civil aircraft communications systems	Civil Aircraft	EIS 2020+
		Dassault Av.	IR architecture, concepts and implemented functions	Business Jet Aircraft	Business Jet Aircraft	TBD according to technologies and concepts maturity
	Mobile IP-SNDCF	SITA	Specification and test results	aeronautical air and ground routers, ground routers, overall architecture		TBD according to regulations and ICAO/standardization activities - 2020?
	Mobile IP-SNDCF & Multi Air/Ground Link Support	Airtel ATN	Specification and test results	Airborne and Air/Ground ATN Routers. For new Air/Ground links such as SATCOM.	Airborne Atn Router and Air/Ground Routers. Data Link Test Equipment.	2017 for operational system based on SESAR/ESA/INMARSAT Iris Precursor Project. Prototype by 2014/5.
	AeroMACS	Airtel ATN	Specification and test results	Airborne ATN Routers & Airport Air/Ground Routers	Airborne Atn Router and Air/Ground Routers.	TBD. Depends on adoption of AeroMACS for ATS Services by AIRBUS and other avioncs manufacturers.

SP4	IMR prototype (inlc. CPRI and Radio Proxies)	Thales UK	IMR technologies, and detailed implementations. Including use of CPRI.	Communications sytems for civil aircraft	Civil Aircraft	EIS 2020+
		Selex ES	CIPRI interconnection between AeroMACS Base Band and RF	AeroMACS terminals	New AeroMACS product line	2015
		Dassault Av.	IMR architecture, concepts and implemented functions	Business Jet Aircraft	Business Jet Aircraft	TBD according to technologies and concepts maturity
SP5	Optical Beamforming Network (including optical modulator)	LIONIX	Panthera (of which LioniX is a 100% daughter company) started a new company "SATRAX" in 2009 which focusses on the further exploitation of the Micro Wave Photonics technology LioniX developed in multiple projects (a.o. SANDRA) Via SATRAX: true-time-delay-based electronic beam-steering antenna systems Micro Wave Photonics components based on the developed photonics technology	real-time broadband SatCom applications for high-speed vehicles.	New Micro Wave Photonics based (satellite) communication products	2015-2017

		ACREO	1. High speed electro-absorption modulators and modulator arrays 2. Packaging and interconnection of high speed electro-absorption arrays	Free space optical communications	Acreo's EAM technology offering	2015
	Antenna Front End (both RF front end and array antenna)	IMST	Basic knowledge on highly integrated RF-modules for agile antenna frontends	Satcom-on-the-move products and radar applications	Prototyping only at the moment	Earliest 2017
SP6	Airborne and Vehicular AeroMACS terminal prototypes, AeroMACS Ground Station	Selex ES	Basic Knowledge acquired during AeroMACS prototype development and integration	AeroMACS Mobile Station Airborne, Mobile Station Vehicular, Base Station, Fixed Station terminals	AeroMACS product line (new)	2016 fixed services 2017 mobile services
		Dassault Av.	Aeromacs potential operating domain and associated performances/constraints	Business Jet Aircraft	Business Jet Aircraft	TBD according to technologies and concepts maturity

AeroMACS network integration (Terminals, Ground Station, ASN-GW, AAA server, test equipments)	Selex ES	Basic Knowledge acquired during AeroMACS prorotype network integration	AeroMACS network planning, implementation and integration services	AeroMACS Network Integration services (new)	2015 fixed services 2017 mobile services

5. Project public website & contacts

Project public website: www.sandra.aero

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Table 4: list of beneficiaries and contacts