Integrated Wireless Sensing

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Compiled by: Bernard BALDINI [DASSAV]

Technical Approval: Philippe LE VAN [DASSAV]
All partners

Issue Authorisation: Bernard BALDINI [DASSAV]

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Integrated Wireless Sensing

Summary

This document provides the final PUBLIC activity report of WISE project:
- project overview: description & objectives, contractors involved, work performed and methodology
- certification aspect: result of discussion with EASA on wireless system for aircraft system monitoring
- evaluation results: overview of Falcon 7X business aircraft and NH-90 rotorcraft testings (detail results remain confidential in Deliverables D6.3.1 and D6.3.2)
- achievement to the state of the art
- assessment towards project Technical Objectives
- assessment towards project Top Level Objectives
- assessment towards project Research Objectives

In conclusion, recommendations are provided for development for a follow-on research project or direct application in a development product for an aircraft application.

Integrated Wireless Sensing

CONTRACTOR INVOLVED

Company	1st Name	Family name	e-mail	Phone
DASSAULT AVIATION	Bernard	BALDINI	Bernard.Baldini@dassault-aviation.com	+33 (0)5 56 13 96 18
EADS-IW	Josef	SCHALK	josef.schalk@eads.net	+49 (0) 89 607 29235
EADS-IW	Martin	KLUGE	martin.kluge@eads.net	+49 (0) 89 60720624
EADS-CRC	Josef	SCHALK	josef.schalk@eads.net	+49 (0) 89 607 29235
EADS-CRC	Martin	KLUGE	martin.kluge@eads.net	+49 (0) 89 60720624
EUROCOPTER	Christian	MONIVAS	christian.monivas@eurocopter.com	+33 (0)4 42 85 68 67
MESSIER-BUGATTI	Jean-clair	PRADIER	jean-clair.pradier@messier-bugatti.com	+33 (0)1 46 29 48 65
MESSIER-BUGATTI	Thomas	LAVAUD	thomas.lavaud@messier-bugatti.com	+33 (0)1 46 29 48 16
TES ELECTRONIC SOLUTIONS	Djordje	SIMIC	djordje.simic@thales-ee.com	+49 711 728 759
TES ELECTRONIC SOLUTIONS	Veselin	BRANKOVIC	veselin.brankovic@thales-ee.com	+49 711 728 762
BRNO UNIVERSITY OF TECHNOLOGY	Cestmir	ONDRUSEK	ondrusek@feec.vutbr.cz	+420541142463
BRNO UNIVERSITY OF TECHNOLOGY	Pavel	FIALA	fialap@feec.vutbr.cz	+420541149510
ADVANCED COMMUNICATIONS RESEARCH AND DEVELOPEMENT S.A.	Alvaro	ALVAREZ	alvaro.alvarez@acorde.biz	+34 942 200923
CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE (CSEM)	John	GERRITS	john.gerrits@csem.ch	0041 32 720 5652
TELETEL	Vangelis	KOLLIAS	V.Kollias@teletel.gr	+30 210 698 3393
UNIVERSITY OF VARSAW	Wojciech	GWAREK	gwarek@ire.pw.edu.pl	(+48) 22 660 77 25
UNIVERSITY OF VARSAW	Pawel	KOPYT	pkopyt@elka.pw.edu.pl	(+48) 22 660 73 47
UNIVERSITY OF SAARLAND	Helmut	SIEDEL	seidel@lmm.uni-saarland.de	+49 (0)681 302 3979

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ABREVIATIONS

Acronym	Translation
UWB	Ultra Wide Band
FBW	Flight-By Wire
FBWS	Flight-By Wire System
RF	Radio Frequence
MTBF	Mean Time Between Failure
SWP	Sub-Work Package
WP	Work Package

1 PURPOSE

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The "proof of concept" conducted by WISE project and associated certification and evaluation results are based on the following application scenario of WISE technology specified in confidential deliverables D2 and D2.2 for Electromagnetic requirements:
- ASF1: wireless slat temperature sensing for anti-ice system (ground and flight evaluated on Falcon 7X s/n 001)
- ASF2: oxygen bottle wireless autonomy monitoring (only laboratory feasibility assessed)
- ASR5: engine air intake temperature wireless sensing (ground evaluated on NH-90 and flight evaluated for energy scavenging from vibration)

ASF1 and ASF2 application scenario were presented to the EASA with an associated certification plan in order to collect EASA feedback.

ASF1 and ASF2 uses RF remote powering technology.
ASR5 uses RF Long range technology associated with energy scavenging technology from vibration.

In addition, for equipment laboratory demonstration of Ultrasonic technology, the application scenario ASF3 called "Hydraulic accumulator energy monitoring" was used.

Justification of the choice of these application scenario and associated test plan are available in confidential deliverables D6.1.x.
Each Technology study and applicability analysis and report are available in confidential deliverable D3.6/D4.6/D5.6.

The exploitation and dissemination plan is available in public Deliverable D7.2.

An executive summary of all confidential deliverable and the power point presentations of WISE final conference and exhibition are available on the WISE PUBLIC web site
www.wise-project .org

2 PROJECT OVERVIEW

This chapter recalls what the WISE project is about, its objectives and how it is organised, as well as the work performed and the methodology used.

2.1 Scope And Objectives

Current aircraft monitoring systems use sensors hard wired to their electronic acquisition unit.

- It precludes acquisition of major parameters where wires cannot be installed.
- It results in complex installation
- It results very often in increasing weight

Current Wireless technologies enable an easy and flexible installation, but their current technology design does not match aircraft monitoring needs as :

- autonomy is limited and power re-loading is requested
- compatibility with harsh aircraft environment is not reached.

Matching aircraft constraints and power autonomy is targeted for wireless monitoring systems, as they request operating at low data rate.

WISE researches the way to integrate wireless technologies, in the aircraft systems environment, **for which the sensor powering has to be autonomous.**

WISE technologies are usable in any fixed-wing aircraft or rotorcraft.

The **project "Objectives"** are to :

- enhance aircraft system monitoring by developing concepts based on new wireless technologies and integrated sensing solutions :
  with autonomous sensor powering and low consumption
  compatible of the harsh environment of aircraft systems
- allow the monitoring of parameters that are not available or hardly available by physical link such as wiring or fluid connection
- replace or simplify wiring solutions, fluid connections
- allow continue monitoring or improve redundancy when, with the physical solutions, the link would be stopped (wire cut, fluid line damaged or destroyed) (ex : fire event, engine rotor burst event). Consequently, wireless networks and wired networks could then be mixed to achieve essential or critical safety levels.
- improve information segregation : wireless technologies allow to save wiring routing space which shall be taken to improve the segregation of other wired power or signal information lines.

Current wireless technologies, which are used in different commercial applications, are not directly applicable as they are not compatible of the constraints of the aircraft systems. On the other hand, neither it is acceptable to wire the sensor to the aircraft power (no power available at sensor level location), nor to embed a battery that will have to be changed frequently for obvious maintenance reasons or simply for harsh environment reasons (high temperature, …).
An autonomous wireless power solution is needed.
In addition, for aircraft systems, low data rate information is exchanged.
These technical main requirements are key motivators for setting WISE objectives.

Combining autonomous sensor powering at low consumption and low data rate transmission compatible of aircraft environment is the guideline research for new "integrated wireless sensing" concept of WISE project.

WISE researches the adequate management and wireless transmission of power between the sensing element and the information receiver, and also the usable reception technique of the sensed information.

The technology "Objectives" are :

- to develop a Radio Frequency (RF) transmission through open air medium that can remotely power the sensing element (WP3). Necessary for applications which preclude a battery use at sensor level, it is usable in an aircraft or in an equipment when no main metallic obstacles exist between the sensor and the receiver locations and on short distances.
  Here the sensor will receive energy from the receiver unit which is connected to the aircraft systems. The level of energy received is low but compatible of aircraft systems application and sensor consumption has to be optimised. The adequate technique to send back the information will be investigated.
- to develop a RF technique of transmission through complex environment for metallic or composite aircraft structure (WP5). This technique should allow to cover communication over the air within the complete aircraft. Here an energy source is locally available at the sensor level, and the signal information is exchanged between the sensor (or a few sensors) and a main receiver. A robust RF technique has to be developed by application of ultra-low power consumption communication technologies to aircraft environment.
  Self-power generation will be investigated and could be integrated at the sensor level.
  Ultra-low power consumption techniques and optimisation will be research to allow long term duration of battery usage when compatible with aircraft maintenance objectives and aircraft environment requirements.
- to develop a technique capable of energy and data transmission through a close metallic envelope (WP4). Usable to monitor parameters inside the completely close metallic envelope of an equipment. Non-RF techniques such as ultrasonic technique will be investigated, including the coupling with power generation techniques.

COTS sensor will be selected and packaged with the developed technologies for the needs of the project.
These techniques have to

- integrate the sensing element at the sensor module level with the chosen wireless techniques.
- match the harsh aircraft systems general environment specification (Eurocae/ RTCA requirements such as DO-160 guideline) and additional EASA/ JAA/ FAA special conditions such as Electro-Magnetic requirements.
- ensure the solutions are robust and secured to jamming.
- ensure the solutions are durable and can cope with the electronic component market quick turn-over.
- ensure costs competitiveness

The research "Objectives" are :

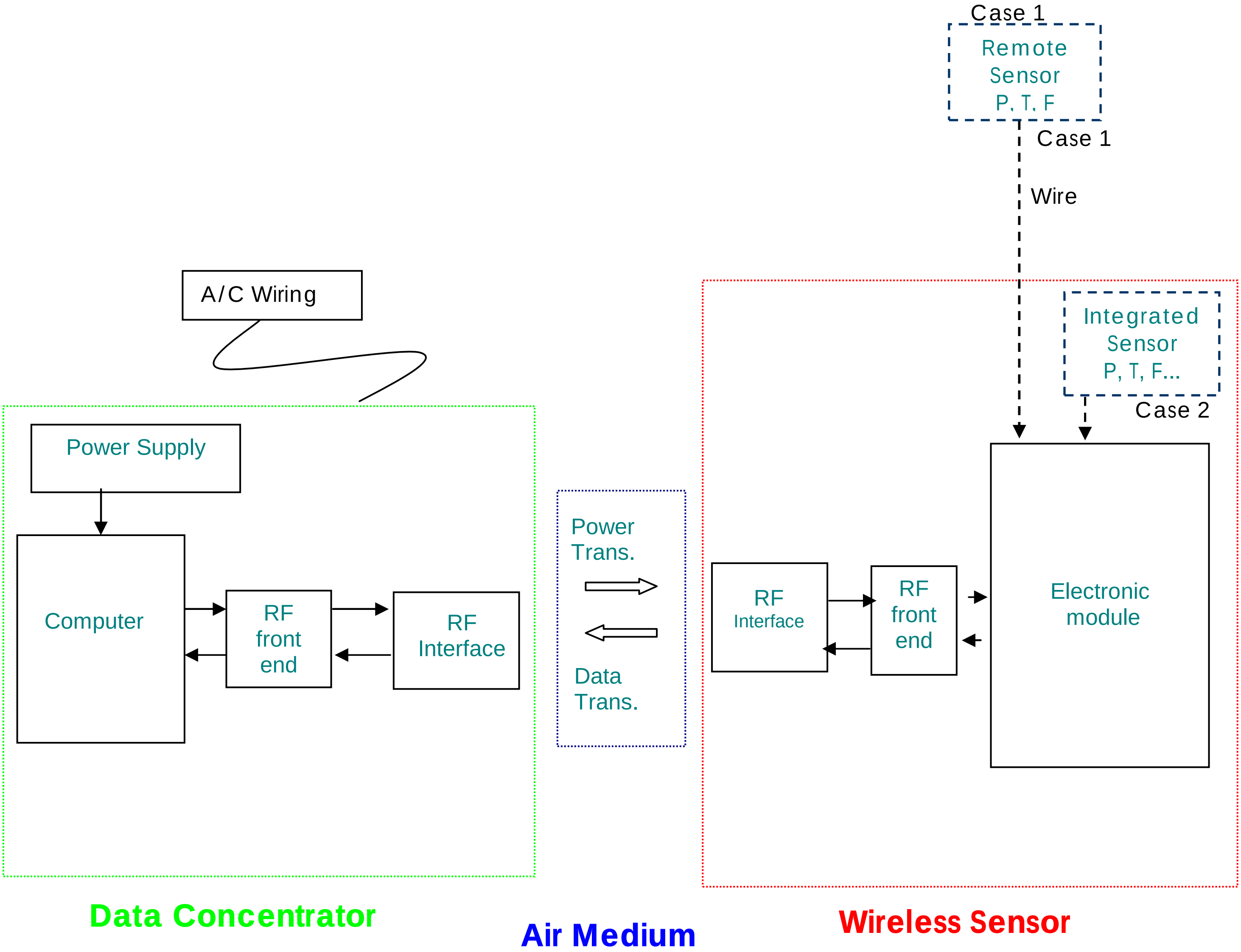
- to strengthen the competitiveness by:
  - reducing aircraft operating cost (Direct maintenance cost reduced as WISE allows maintenance on condition, simplifies aircraft installation)
  - improving availability/dispatch rate through better maintenability or reliability
  - reducing installation cost: complex/moving parts, within composite structure
  - reducing cost of ground & flight test installation
- to improve safety and security by:
  - improving Man Machine Interface:
    - better situation awareness
    - simplification of Air Flight Manual or Maintenance procedures
  - contributing to the reduction of accident rates by:
    - removing sensitive wiring routines
    - improving failure rate by usage of wireless sensing
    - improving fire protection: reducing source of oxygen leakage, removing holes in composite structure

2.2 Integrated Wireless Sensing Definition

Applicable technologies are :
- WP3 : Transmission through air medium (Radio frequency remote powering)
- WP4 : Transmission through metal envelope (Ultrasonic)
- WP5 : Transmission through complex environment (RF long range)

For the WISE technologies, we use the following definition :
- LRU connected to the aircraft power and data network : DATA CONCENTRATOR
- LRU not connected to the aircraft harness that senses the information : WIRELESS SENSOR, including an electronic module and a classical sensor embedded in the wireless sensor or wired to it.
Both LRU constitute one Integrated Wireless Sensor (WISE sensor).

In WP3, the data concentrator transmits energy to the wireless sensor by RF means and receives by back scattering techniques the sensed information. It is a point to point communication.



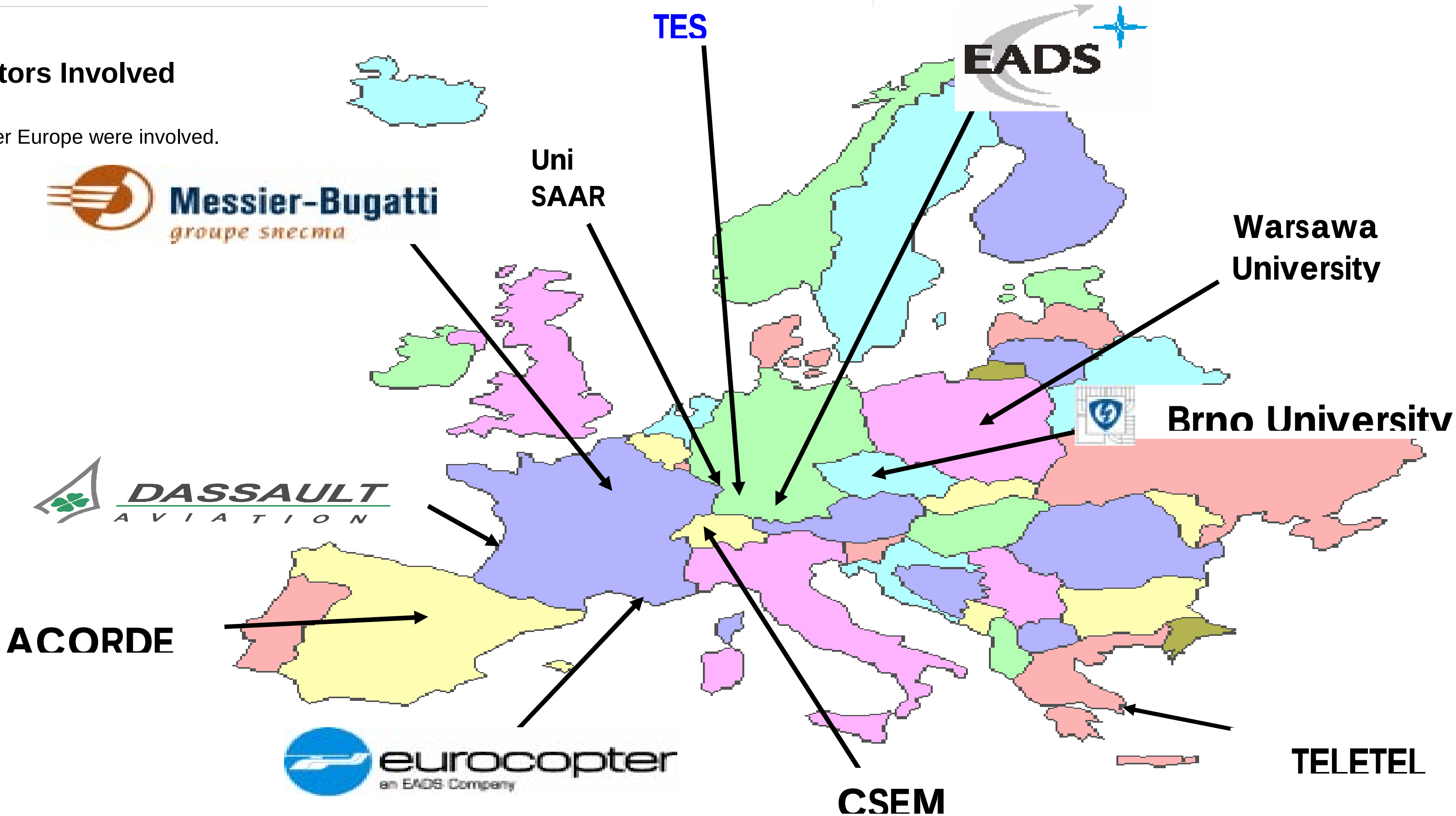
In WP5, the sensed information is still received by the data concentrator but, due to distance, the wireless sensor has its own source of energy (self-power generator with or without battery or super capacitor if allowed). Data concentrator send RF interrogation signal to its wireless sensor (max around 20 per data concentrator). A single wireless sensor can also send information to a fix and a portable data concentrator used by maintenance people (ex: oxygen bottle pressure)

In WP4, the sensed information is exchanged with the data concentrator by ultrasonic means. The data concentrator sends an ultrasonic interrogation signal to the wireless sensor and retrieves the sensed information. The exchange of energy between the data concentrator and the wireless sensor is achieved by ultrasonic means. It should also be investigated if it has its own source of energy, e.g. by its ownpower generator with or without battery or by a super capacitor if allowed).

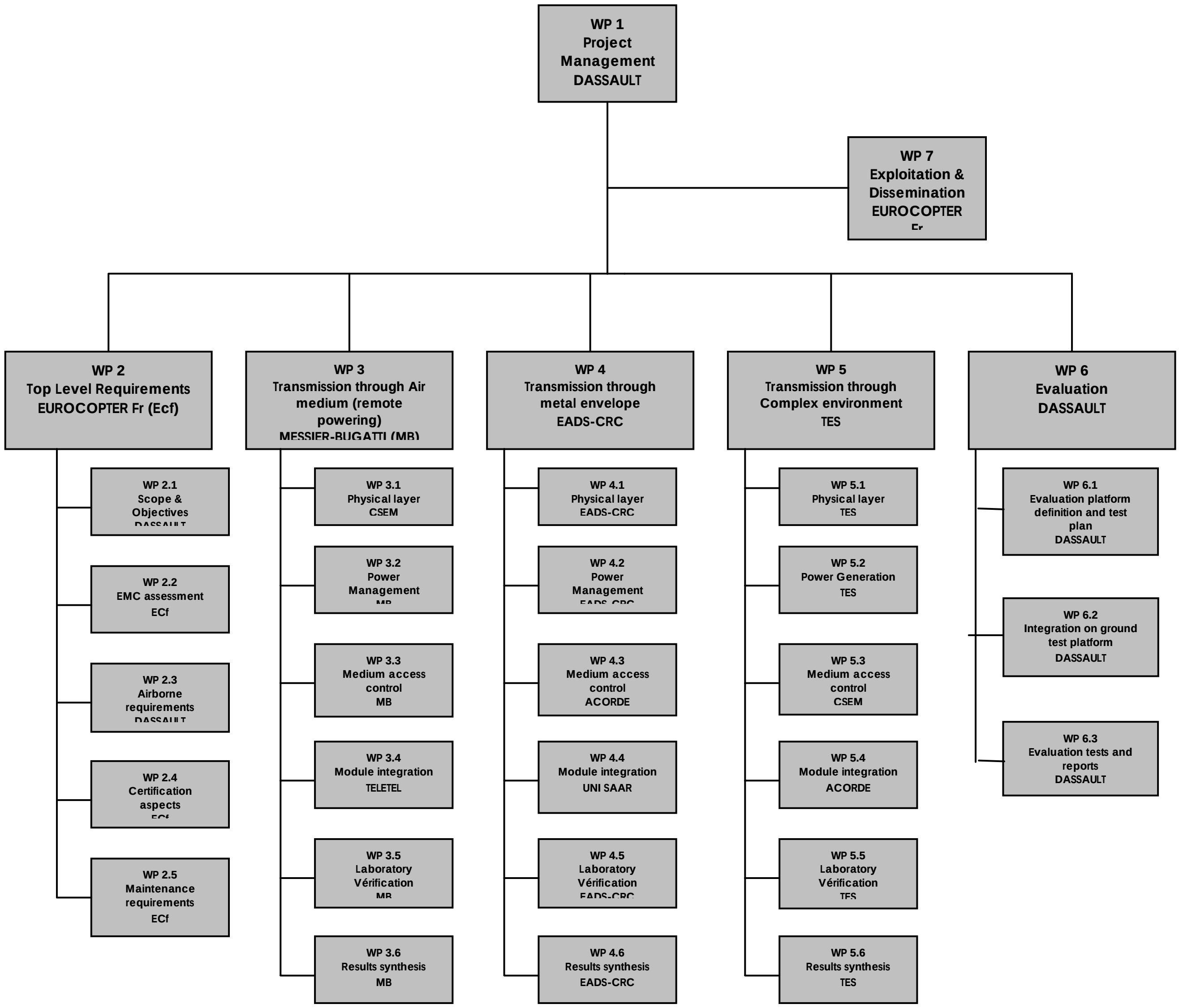
Sensed data by wireless sensor is limited to 3 different datum amount, for example : temperature, pressure, level/position, strength, fire status…etc
For customer aircraft application, the scope of data rate targeted are generally low to ensure compatibility with the technologies and airborne maintenance or environmental temperature that could prohibit the use of batteries.
With higher data rate (flight test application for example), batteries or super capacitor may be allowed but a self-power generator is preferable when sufficient vibration allows its usage.

2.3 Contractors Involved

11 partners, all over Europe were involved.



Research task force included 11% of University, 12% of Laboratory, 16% of SME, 62% of Industry partners that are organised around the following breakdown srtructure.



2.4 Work Performed And Methodology

The work methodology includes:
- scope and objectives re-defitnion at project start
- a specification phase where the aircraft manufacturer issued the specification documents. Leader of technology WPs were involved at the stage
- selection of relevant scenarios for technology "proof of concept"
- theoretical feasibility by computation/ simulation
- development and partial verification by laboratory tests on mock-ups when necessary
- partial validation tests or measurements on the real aircraft during equipment development
- final equipment qualification of the evaluation prototypes (limited to pressure/altitude, temperature, vibration, EMI/HIRF, Lightning)
- final functional and Electromagnetic validation on aircraft during ground and/or flight tests
- final assessment of results toward the objectives

During the project:
- 3 preliminary EM measurement campaign have been performed on business aircraft and rotorcraft
- about 4 o 5 sets of prototype equipment including various version of power generators have been manufactured to support :
    - the debugging/optimisation work
    - the equipment qualification
    - and each aircraft testing
- a part of slat mock-up has been realised
- many laboratory tests have been performed during the development phase to make partial validation or controls with light tests means developed
- laboratory tests have also supported the equipment manufacturing debugging
- at total of 3 final ground tests sessions and 2 non specific test sessions have been organised on business aircraft and rotorcraft

3 CERTIFICATION ASPECTS

Following discussions with EASA based on certification plans provided and additional material such as safety analysis, test plans or reports, EASA gave the following coments for an aircraft application.
The certification plan provided for usage of wireless system in aircraft system were found acceptable, even for a critical application pending that the reliability is correctly demonstrated by an edequate plan for such a novel technology.
The EASA would write a CRI (Certification Review Item) for the novel aspects of such a certification application.

NB: EASA has even found better some solutions than the actual ones: eg. "Oxygen Bottle Wireless Autonomy Monitoring"

During the WISE final conference, it has been pointed out by Dassault Aviation participant that, for Remote Powering, in case the RF power emission frequency shifts from its assigned frequency, it could interfere with other radios or systems. This shall be considered in the certification process: such an event should classified in the relevant "Failure Hazard Analysis" resulting from the analysis of the consequences at aircraft level, and treated in the technology design by matching the required failure rate or making it impossible.

Such item should be required by the CRI.

4 EVALUATION RESULTS

4.1 Falcon 7X Evaluation Results

4.1.1 Functional tests

The ground functional tests consisted in checking that the temperature is correctly calibrated, as the good accuracy and the the information is never loss on ground or in flight and during slat motion.

The WISE temperature is correctly calibrated and the WISE system has a maximum error of +/- 0.3°C (COTS temperature sensor accuracy not included) and +/-0.1°C in average which is satisfactory.

On the aircraft, the difference between WISE system and basic functional system is:

- 0.2°C in flight
- 1.5°C in ground/taxi phase
- 1.3°C during the ground tests

The result is satisfactory in flight. The sensed temperature also differs from the basic system due to the location of the WISE COTS temperature sensor on the slat itself.

The temperature information on the ARINC bus is never lost on ground during slat motion, however it is lost in flight when slats are extended and continues to be lost in flight or on ground until slats are retracted.

Based on the qualification tests, the root causes could be:
- loss of W/S wireless temperature signal was experienced during temperature variation test. This can be caused by an inadequate power transfer level to the W/S part, in conjunction with thermal lag in the W/S and/or DC (thermal management has not been taken as a design driver from project start due to project priority). In flight, when slats are extended there is a rapid decrease in temperature.
- interference problem with VHF system as the EMI qualification test shows that the external temperature wiring linked to the W/S unit act as an antenna that can collects some perturbations inside the W/S, also the DC power unit is not a full metal box which size is comparable to the V/UHF wavelength and could conduct the VHF interference to the DC main unit. These issue could be mitigated for a product application by filtering at the W/S temperature input, DC units could be also in a unique box.
Unfortunately the real aircraft VHF emission levels are under the level applied during the qualification tests. In addition, the system was always lost as soon as the slats were extended and for most of the case VHF was not in emission. In addition, no interference were observed by Dassault Aviation during aircraft ground EMI tests. So loss of temperature signal is decorrelated from VHF emission.
- another explanation could be water ingestion problem due to humidity in flight as the DC main unit has been founded full of water after the aircraft returned from flight: this does not seem to explain the failure as the system could operate back when the slats were retracted.

It clearly appears that, in flight, the power emission is too low when slats are fully extended, but the root causes have not been investigated due to lack of time between latest flight tests/qualification tests and project end. (inadequate power transfer + thermal lag are suspected?)

NB: it is not considered that the radio-telemetry system interfers towards WISE, as ground measurements show no effect.

4.1.2 Electromagnetic tests

The ground electromagnetic tests demonstrated the absence of interference with radio-navigation or communications systems, aircraft systems or Flight-By-Wires.
The ground tests included static verification in the hangar and ground run verifications.

However, WISE RF remote powering technology interferes toward cabin Mutimedia system or PEDs using WIFI: as the RF remote power emission occupies almost all the WIFI 2.45GHz channels, these channels are not usable for WIFI communication in the cabin (transmission is too low or impossible). Another "free" frequency band should be used for power emission, by WISE RF remote powering technology.

The flight test confirms the absence of interference of WISE towards the aircraft systems, however this has not been checked when slats are extended and WISE power is at its maximum level, as WISE system was lost in this case. WISE interference towards PEDs has not been rechecked in flight as no WIFI multimedia system was installed for the flight tests.
When slats were retracted, no interference towards WISE system was observed.

4.2 NH-90 Rotorcraft Evaluation Results

The EUROCOPTER application was to replace a temperature sensor by WISE.
This scenario was the engine air intake temperature measurement of a NH90 Helicopter using WISE technology. WISE is composed by 2 elements:

- ✓ A Sensor (Wireless part)
- ✓ A Data Concentrator (Part linked to helicopter network power supply)

- The wireless sensor consists in a temperature sensor, a transmission / reception antenna in order to be able to communicate with the Data Concentrator, an electronic board and an autonomous power generator. In this application, the autonomous power generator provides energy with the mechanical energy conversion coming from the vibration of the helicopter. It is tuned at the main frequency of the helicopter that is in this case 17Hz.

- The Data Concentrator linked to helicopter network, consists of a electronic board, of a transmission / reception antenna in order to be able to communicate with the wireless sensor.

Two tests were performed:
- a flight test of the autonomous power generator.
The purpose of this test was to check in flight the conversion of the mechanical vibrations into electric energy.
- a ground test of transmission / reception.

4.2.1 Functional tests

Autonomous power generator Flight Test

The generator was installed in a test electronic box which included an accelerometer and a PC of data acquisition. This test electronic box was fixed in the cabin. The purpose of this test was to check the conversion of the mechanical vibrations into electric energy

This test demonstrated the energy conversion. Obviously this test could not express the optimal conversion because the test electronic box was not fixed at the location of WISE, but that would be the final one because of experimentation constraints. Nevertheless, the test showed that the necessary power level to supply the sensor part was reachable.

Data transmission / reception Ground Test

These tests demonstrated that the temperature data received by the data concentrator evolves according to the temperature applied to the sensor. This test thus demonstrated the exchange of information between the 2 elements.
On the other hand, these tests did not evidence the precision of the data. Unfortunately the electronic board that was available for the tests was not calibrated as a consequence the measurement accuracy could no be demonstrated.

4.2.2 Electromagnetic tests

Most important was to perform tests of internal EMC, the goal is to demonstrate the capacity of the system to work in an electromagnetic environment helicopter and to demonstrate that this system does not perturb the equipment items helicopters including the receivers i.e.:

- Interference effect on the receivers caused by WISE system.
- Interference on WISE system caused by electromagnetic fields of helicopters transmitters (intentional or not)

Wise on emission:
The ground electromagnetic tests demonstrated the absence of perturbation on Helicopter avionics

Wise on reception:
The ground electromagnetic tests demonstrated that WISE is disturbed by Helicopter avionics.
However the state of the project did not allow to conclude on the susceptibility tests because the electronic unit that was delivered for experiment was not compliant with the EM susceptibility requirements. This deficiency has been clearly identified at the level of the casing of the electronic board. Unfortunately, it was not possible to fix the problem during the experimentation period that was constrained by the availability of NH90 helicopter.

5 ACHIEVEMENT TO THE STATE OF THE ART

5.1 Radio Frequency Remote Powering

In the domain of RF Remote powering a step forward has been achieved and the novel aspects have been patented:

1- the fact to have a Wireless Sensor without any own source of energy, that receives its energy sources by Radio Frequency means from a data Concentrator unit and that is able to send back the sensed information wireless to the Data Concentrator unit applied to :
- the acquisition of an information from a moving aerodynamic surface of an aircraft
French Patents number: FR 07/04090 "Procédé pour collecter une information relative à une surface aérodynamique mobile d'aéronef"
- the measurement of the caracterics of a gaz bottle (such as an oxygen bottle for example)
French Patents number FR 07/05047 "Bouteille de gaz équipée d'un capteur radiofréquence"

2- The use of high frequency for remote powering and data transmission as well as:
- the usage of the RFID concept for data transmission to lower power consumption of the wireless sensor unit
- the coding issues and frequency selection stuff
Polish Patent number: PL P384303

It has been explored and demonstrated to efficiently remotely power a sensor with a variable distance up to 28cm with can angle up to 20°between the DC and WS antennae faces and a deflection angle up to 50° (both antenna not facing); and to receive back up to two different informations: temperature in the application case selected. 2 Pressures or 1 pressure + 1 temperature or 2 pressure would also work.

The use of high frequency overcomes the limitations of low-frequency powering, as it is effective only on short distances (some centimeters).

5.2 RF Long Range

The usage of RF technology in long range RF technology has been connected in large extent with possibility to unite data transmission over large distances and enable autonomous powering of the sensor nodes. To demonstrate these features two implementation concepts have been followed.

1. To obtain the data transmission through harsh environment without interference to other on-board systems the implementation of the ultra wideband (UWB) communication system has been made. The system is capable of communicating on 3-5m distances with data throughputs of up to 1 Mb/s using pulse-based UWB technology. It is one of first systems implemented leaning on the IEEE802.15.4a low data rate UWB standard. Since the implementation was based on the non-integrated solution with implementation based on using combination of integrated radio front-end discrete analogue processing circuitry and commercially available digital development platform, it was not suitable for integration on the flying platform due to large size and high power consumption. To overcome that, more mature RF technology based on the commercially available components has been used.
2. The COTS platform has been used to demonstrate integration capability of the radio technology and autonomous sensor powering. The chosen RF technology (IEEE802.15.4, Zigbee) enabled usage of common MAC and application layers to ones used in UWB technology case and later integration of the solution in other technology. The platform was targeted to support ASR5 scenario developed by EC and was capable of integrating two sensor nodes with a data concentrator, operating with peek data rate of 250kb/s. The implementation is operating in worldwide available 2.4 GHz frequency range and was

optmimized for low-power, low duty-cycle operation. Large saving in energy consumption have been reached by implementing optmized MAC and power management functions. The platform functions purely battery operated while beeing on-ground, while during the flight the combination of the energy scavenging and battery operation is going to be used. Depending of the flight phase and available vibration levels, it is predicted to have 30-100% reduction of the instantenous battery power consumption. In mean value, it is expected to have 55-60% exstension of the battery life and maintenance period.

Due to implementation complexity, it was not possible to achieve the reliability levels that are satisfied by counterpart wired solutions.

5.3 Ultrasonic

The WISE US demonstrator has successfully proven the possibility of powering a microcontroller platform and wireless operation of a COTS temperature and pressure sensor inside a conductive envelope by means of accoustic energy transmission and communication, therefore it allows to introduce new measurement applications and to remove classical wire feed-throughs.

In details a power transmission of up to 30mW has been established on a 3MHz carrier (with 80% efficiency). On top of this carrier a half-duplex, bidirectional communication has been achieved with a raw data rate of 1kbit/s. The low parts count of the integrated electronics in combination with a reliable packaging technology (LTCC hybrid) allows to reach a high reliability with a MTTF of more then 100.000h. The reliability of piezo attachment has been validated by accelerated testing. Further verification tests have shown that the design is insensitive to aircraft structural vibrations (< 2kHz, 8 grms) and that it is able to survive storage temperature from -55°C … +85°C. First prototypes have been found to be operative within a temperature range of [-5,+30°C].

5.4 Energy Scavenging & Power generator

During the WISE project an electromagnetic energy harvester and a power management circuit have been developed. They allow to recover electrical energy from the vibrations of the main rotor of a helicopter and to power a wireless sensor node. The generator operation has been validated in laboratory and demonstarted during a short test flight. The device is capable of providing 3 - 25 mW out of 0.1 – 0.4(and higher) grms vibration range and thus it is capable of extending the service interfall of the wireless sensor. The extending depends on level and stability of vibration. The stable vibration level 0.4 grms can provide 100% energy for the wireless sensor. Using optimized power management circuit and older, less sensitive generator version (8mW@0.3 grms) it was evaluated that the saved part of the battery energy is, for the vibration spectrum delivered by Eurocopter, at least 50%. Using the last generator version mentioned above the result is significantly better.

6 ASSESSMENT TOWARDS PROJECT TECHNICAL OBJECTIVES

The speficiation phase of WISE project showed that, whatever the applications, most of the time, common requirements and design drivers are requested for each technology: they are summarised in the targets column. The assessment performed within WISE project is given for each Aircraft type.

REQUIREMENTS	TARGETS	FIX WING BUSINESS A/C ASSESSMENT	ROTORCRAFT ASSESSMENT with RF Long Range
RF transmitted power	< 100 mW (Eirp)	Correct operation in Lab, on A/C during ground test, on A/C flight test only with slats retracted	Achieved
Failure Rate	3 10E-4 to 10E-5 pending system application	1- RF technologies satisfies requirement << 10E-5 2- For Ultrasonics, very good MTBF on sensor part sealed in the equipment (few electronics) 3- Requirements shall be minimized by working on a/c system architecture or use of non COTS sensors (less electronics on wireless sensor side)	
Accuracy	+/- 1°C	Remote powering: +/- 0.1°C average, +/- 0,3°Cmax added to COST sensor accuracy of +/- 1°C Ultrasonic: accuracy of the sensor used	Not achieved BER and accuracy could be improved
Weight	100-200g max (not over a wired solution)	Not achieved	
		Remote Powering: Requirement shall be achievable by a design adapted to each application, with the use of Non COST sensors Ultrasonic: Target weight acheived	Weight reduction by using more advanced materials in power generator construction and electronics design optimistaion to reach about 350 g
Operational temperature	+85°C max continuous (+125°C short time explored)	Remote powering: to be performed Requirement can be limited to +85°C max or less pending applications by working on equipment integration to the aircraft structure Ultrasonic: survival temperature test passed, operational temperature range is currently limited (-5°C ... +30°C)	Not achieved due to: - unkown electronic solution at the project start - use of commercial grade component
Sampling rate	up to 2 Hz for fix wing a/c up to 200 Hz for rotorcraft or flight test applications	Achieved NB: higher data rates applicable for Flight test applications but implies maintenance action	
Maintenance	Condition monitoring No additional maintenance must be required	RF remote powering: Achievable by principle (no battery usage, imune to dust, matching required failure rate) Ultrasonic: Achievable for the wireless sensor part sealed in the equipment	1- Not achieved due to too short primary battery cell maintenance cycle. 2- Improvements possible by sensor power consumption operational optimisation and usage non COTS components
Criticity	Non essential to Critical Systems	Achievable pending Failure rate and MTBF are well justified by an adequate demonstration plan for such a novel technology (EASA feedback)	

7 Assessment Towards Project Top Level Objectives

WISE achieved the following project objectives:
- improve aircraft monitoring by developing concepts based on new wirless technologies and integrated sensing solutions with autonomous sensor powering and low consumption: this has been achieved for each technologies
- allow to monitor parameters not available or hardly available by physical link (wire or fluid)
- replace or simplify wiring solutions, fluid connections
- information still available after wire cut (by design!)

WISE achieved partially the following project objectives
- improve aircraft monitoring by developing concepts based on new wireless technologies and integrated sensing solutions compatible of harsh environment of aircraft systems

- for RF remote powering: For EMI/HIRF tests: all passed, except that for HIRF radiated test the external temperature sensor wiring acts as an antenna and therefore the system is vulnerable to V/UHF emission: a correct shielding of the cabling plus filtering in the W/S would solve this issue. Also the DC power is not a full metallic box.

For Electrical tests that involved insulation, bonding and power input tests, WISE set passed successfully through all them.

For the Environmental tests per DO-160E requirements: the qualification test performed showed that the system is compliant with the vibration requirements. During altitude testing, the WISE set did not present any signs of malfunction. Temperature tests presented problems in high and low temperatures. During high temperature tests, when the test chamber temperature was 125^{o}C, the WISE set operated for a short while, then the sensor accuracy presented degradation and finally the set stopped. It is suspected that this was due to the fact that certain components are commercial grade and thus the problem can be overcome by more carefull components selection. At low temperatures, the set operated normally at the lowest extreme (-40^{o}C) but communication with the remote sensor (WS) was lost or erroneous at temperatures between the extremes during temperature variation test with some partial recovering at some temperatures range. This problem is not due to components rating, but is most probably related to the RF power transfer from the DC MAIN to the remote sensor module and can be resolved by updating the DC MAIN microcontroller software. Inadequate thermal management and thermal lag in the W/S sensor is also suspected.

- for Ultrasonic: Verification tests have shown that the design is insensitive to aircraft structural vibrations (< 2kHz, 8 grms) and survives storage temperatures from -55°C to +85°C. However, despite these promising results, some limitations have been encountered: the operational temperature range of the first prototypes has been found to be -5°C to +32°C (for communication) and the EMI compatibility of the data concentrator still requires improvement. It is expected that these challenges can be overcome by a redesign of the data concentrator by introduzing means of temperature correction and by adding a metallic shielding and EM-filtering of the supply lines.

- for RF long range: it did not achieved the temperature requirements due to use of commercial grade components. After temperature tests, just non-invasive tests like EMC and radiated interference tests have been performed in order to preserve the devices form damage for functional tests. EMC test passed. Power generation circuitry have been commited to vibration tests and the tests have been passed successfully.

WISE did not achieved the following project objectives:
- enhance information segregation (no wide aircraft application identified for WISE technologies, not interesting to mix wired and WISE technologies for a system development cost aspect)

8 ASSESSMENT TOWARDS PROJECT RESEARCH OBJECTIVES

The gains of WISE technology really depend on each application cases.

Currently, as no wide application has been identified for WISE technology in the aircraft system, a general quantified assessment cannot be given, only a qualitative global assessment can be given.

The main gains identified are as follow:
- reduce aircraft operating cost and installation costs: WISE allows a simplification of installation and/or layout in the aircraft, it also allows a maintenance on condition that reduces direct maintenance costs
- improve availability & dispach rate through a simplification in system maintenance (cancellation of interconnection wiring for moving or removable parts, or simplification in maintenance see below)
- reduce cost of ground and flight tests installation thanks to wire removal
- improve rotorcraft performance (thank to improvment in air intake temperature sensing accuracy)

- improve Man Machine Interface thanks to
    - a better situation awareness, as WISE allows to access to the exact energy status of the aircraft systems
    - a simplification of AFM/maintenance procedures: when WISE technology allows to access to the exact energy or status of the system which is not currently available with a wire solution, preventive maintenance actions or pre-flight checks are removed
- reduce incident or accident rate thanks to :
    - removal of sensitive/moving wiring routines
    - reduction of incident due to gas or fluid leakage by cancellation of derivation/access used for aircraft system monitoring
    - improving fire protection by removing of holes to pass the wiring through rotorcraft composite sections

9 CONCLUSION AND PERSPECTIVES

The project has shown that using wireless techniques in aircraft system monitoring is very interesting in some specific application cases, as long as it does not exceed the required failure rate of the corresponding system safety analysis.

The 3 "WISE technologies" explored largely cover the aircraft needs:
- Radio-Frequency remote Powering (for distances up to 30cm)
- Radio-Frequency Long Range (for longer distances)
- Ultrasonic (to pass through a metallic envelope with thickness of 7mm)

The WS element packaging of the Ultrasonic technology has been made in a very simple and matching the reliability objectives as few electronics is needed, it could be easily sealed in a close metallic envelope.
The associated demonstrator has successfully proven the possibility of powering a microcontroller platform and wireless operation of a COTS temperature and pressure sensor inside a conductive envelope by means of accoustic energy transmission and communication. The technology developed has the potential to reduce installation costs and complexity and it is close to be ready to be implemented into a first non critical application, like for example the hydraulic accumulator monitoring or a flight test installation.
Two hurdles that still need to be overcome are the expansion of the operational temperature range and the improvement of EMI compatibility, but with a redesign of the data concentrator, it seems feasible to reach a adequate solution in the near future.
In parallel to commercialization, additional work in future also may be focused on further increasing the data throughput and on increasing the energy that is transmitted.

EASA has found acceptable usage of wireless sensing in critical function performed by aircraft systems, pending their failure rate is correctly demonstrated by an approved plan. Also, the probability to have a shift of the RF transmitted power, from it assigned frequency, should be very low or made impossible by design.

Current aircraft integration aspects and COTS sensor integration prevent from having a standard or main partial standard WS or DC design.

With the current design of aircraft systems, extensive usage of wireless techniques is not an evidence.
No business case that could drive the cost low, has appeared.

The only domain for which a larger application of RF wireless sensing can be found is the flight test installation for which the requirement to cancel the wiring is strong and the required failure rates are less stringent. However higher sampling rates are usually needed compared to aircraft system applications, which means higher energy consumption at sensor level for a COTS sensor.

Also candidate application will certainly spread over with the use of simpler sensors (not COTS ones) that will allow to improve the failure rate (by requiring less electronics at sensor level) and simplify the aircraft integration solutions.

Beside WISE "proof of concept", to get on board a RF remote power application at such distances explored by WISE(up to 30cm), RF power emission cannot be done in WIFI as it interfers with cabin PEDS, and should be done in a band not occupied by airborne systems, with optimise impact on antenna size.
This implies:
- to emit power in a well controlled EMC environment that will avoid functional re-validation tasks when new cabin PEDS or radios are installed
- FCC&CEI acceptation
- redesign of antenna, transmitter and receiver

The implementation of WISE RF long range technologies can be envisioned in several cases which include scenarios that have not been directly considered in this work including:

- Temporary sensor networks, used during system development, test, service and/or maintenennace
- Cabin systems for communication and information exchange between the flight personel, infrastructure and passengers.
- Sensor systems with low sampling rates used in application with relaxed failure rate conditions

It is not expected that evaluated long range technologies could replace existing solutions in cases considered during this project, since the benefits of the technologies are masked with increased system complexity.

Usage of energy scavenging methods promises implementation in application scenarios with stable source conditions (e.g. vibration, light, air flow or similar) or using combination of one or more of these sources with a conventional battery operation in cases where wired installation is too complicated. WISE demonstrated energy density of vibration based energy scavenging that is on top of present state-of-the art performances. Further investigation in material use and size reduction can make this technology everyday thing in future applications.

Future research or application in aircraft product for an aircraft systems application shall address these items to make WISE a reality on board of an aircraft.