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AirWISE

Deliverable D1.1

Final Report

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Abstract

This document is the official final report on the Cleansky JUT project AirWise, as required by the European Commission. It corresponds also to deliverable WP1.1 “Project report” of the project’s list of deliverables.

The AirWise project aims at developing a generic hardware platform for airborne WSN nodes. The project started on the 1st of December 2009 and finished on 30th of November, 2010. The report follows the template published by the European Commissions. The topics covered are: executive summary, context and objectives, main S & T results / foregrounds and potential impact.

Keyword list

Wireless Sensor Networks, Airborne, TinyOS, Zigbee, Low-power, PCB modules

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1 Executive summary

The AirWISE project successfully studied, designed and tested a wireless sensor network node platform for operation in airborne environment and powered by batteries. In parallel a study of energy harvesting potential solutions versus power consumption of this low-power node has been performed. This study gives some future directions of the energy harvesting application for the autonomous wireless sensor nodes.

The AirWISE platform is derived from an existing IEEE802.15.4 compliant module (ZorgWave) previously developed at CSEM. Given the specific requirements of the AirWISE project and in particular the airborne context, the module had to be tested for conformance to derive the necessary modifications. The tests include conformance to specific chapters of the DO160 standard in terms of unintended emissions and vibration resistance. Resistance to the extended temperature range of +85 to -55 °C has also been verified. Finally, as operations of batteries are planned, energy consumption of the existing module operating in different modes has been measured.

The unintended emission and vibration tests were passed with success. The module was also able to operate over the entire temperature range (+85 to -55 °C) without any noticeable impact on packet transmission. Current consumptions were adequate for battery operations during 18 months and exploitation with energy scavengers was also possible under low duty cycles.

As a result, the AirWISE node retained the ZorgWave circuits and schematics. It was adapted in terms of the mechanical design and connectivity based on the specifications provided by the topic manager. Five samples of the AirWISE node including the ported TinyOS software platform have been delivered to the topic manager (HAI). The final node is illustrated in Figure 1.

The results of AirWISE project have been disseminated with a poster at CSEM booth during the ICT 2010 event in Brussels.

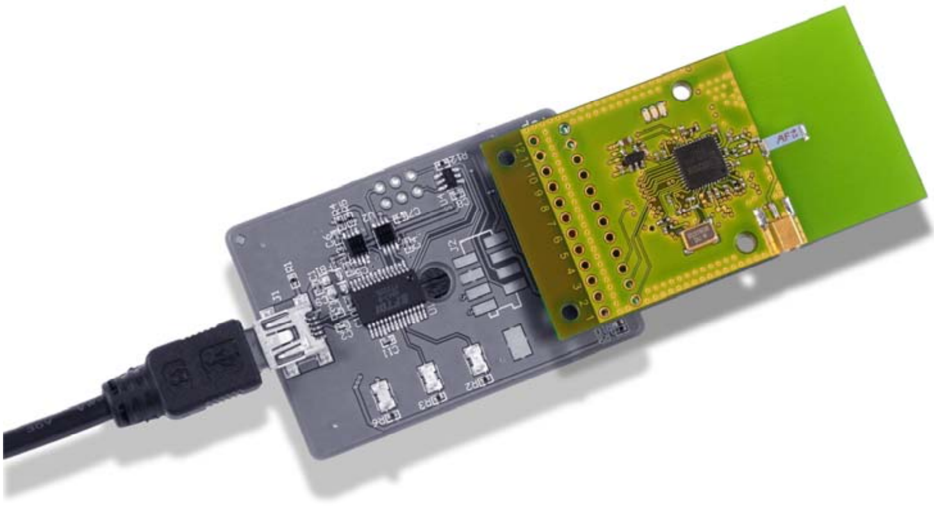


Figure 1 Photo of the AirWISE module/node (green colour PCB) delivered to HAI.

2 Context and main objectives

2.1 Project global objectives

Wireless sensor networks (WSNs) have been an active field of research for nearly a decade. A large number of protocols have been proposed to fulfil the different networking functionalities, physical layer, medium access control, routing, discovery, clock synchronization, etc. IEEE 802.15.4 is the first international standard devoted to WSNs. As all the IEEE 802 standards, it only covers the physical layer and the medium access control sub-layer of the OSI model. This standard has served as a basis for the ZigBee industrial alliance to develop a fairly complete networking solution that includes security, routing as well as service description and discovery. Additionally, a large community, mainly from the research, has developed around TinyOS a number of protocols and WSN solutions. Because of its wide availability and complete openness, TinyOS has been the environment of choice for many research teams that want to demonstrate their ideas. It is flexible and of easy access with a large user community. Today, wired sensors are used for monitoring the condition of aircraft engines, structures, gear boxes, and so on. Wireless sensor network (WSN), i.e., smart sensors with radio interfaces, promises unprecedented operational benefits. Reduced airplane sensor wiring costs & weight because cabling is limited to some specific scenarios and flexibility to be deployed on airplanes without requiring a redesign of data wiring layout are certainly some of important arguments for programs such as Green Regional Aircraft.

In that context, this proposal replies to the requirements described in the Clean Sky Call for Proposals (CfP) referenced under JTI-CS-2009-GRA-01-019 and named “Miniaturized Sensors”. The proposal clearly focuses on building a miniature generic hardware for the airborne WSN nodes. It is based on an existing low-power 2.4 GHz CSEM wireless module (called ZorgWave, see Figure below) with the objective to evaluate and re-design the existing, functional hardware to encounter the limitations and constraints imposed by operation in airborne environment according to FAA regulations.

The design and development of the wireless sensor network hardware has to comply with the requirements described in the call for proposals. In order to fulfil these requirements, in particular those related to the aeronautics environment and regulations, CSEM collaborates with RUAG Aerospace which will be working in this project as aeronautics advisors. RUAG Aerospace will also help in the quality assurance of the project.

2.2 Consortium

CSEM is the coordinator and the only active participant to this small project.

RUAG acts as an advisor in particular their Office of Airworthiness. Several CSEM-RUAG meetings and e-mail exchanges dedicated to the AirWISE project have been organized.

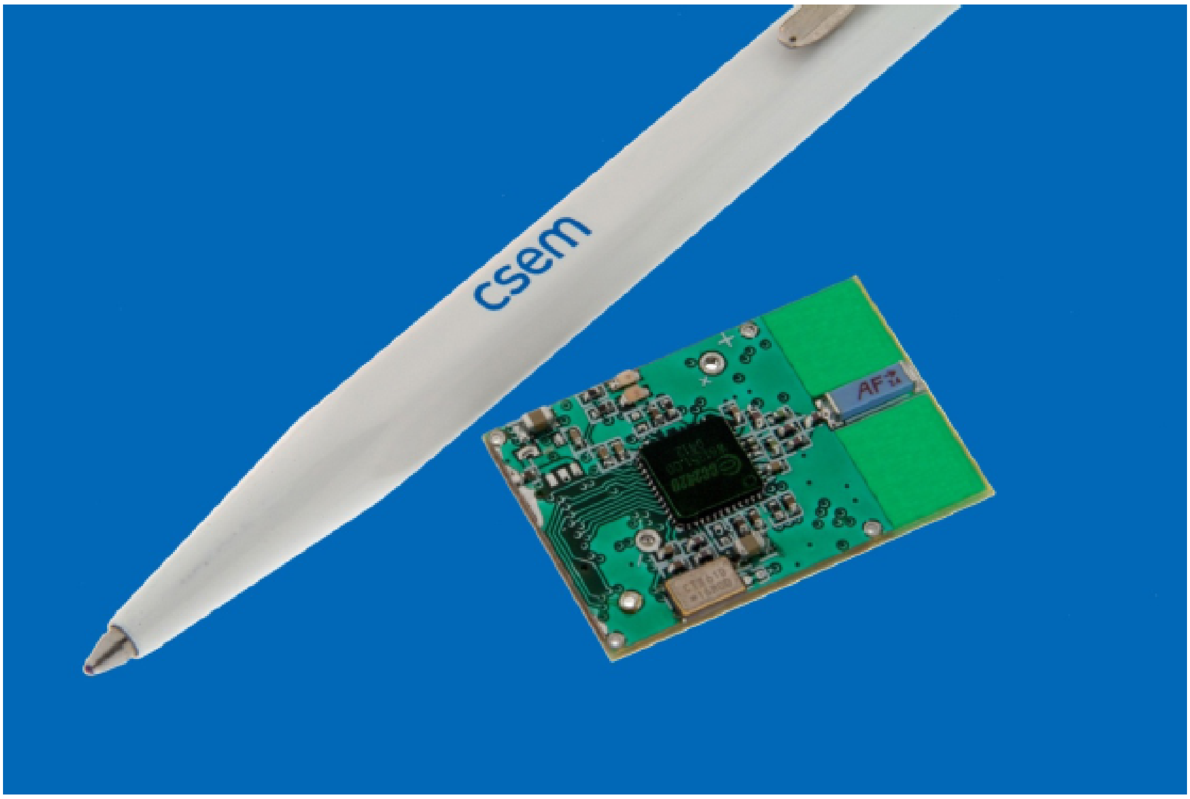
Due to the limited & consulting based implication of RUAG, RUAG suggested collaboration without a formal subcontracting contract signature. Thus, at the end, the consulting of RUAG was done free of charge for the project.

2.3 Project structure

The project was organized in five technical workpackages following a classical sequential model.

WP2 started the project with the evaluation of the requirements and the analysis of the ZorgWave existing module from which we planned to derive the AirWISE platform. Based on the evaluation results, WP3 defines the architecture of the platform and the preliminary schematics. WP4 details the schematics and realizes the hardware. The board is tested in WP5 by porting TinyOS and testing the behaviour when the board is submitted to temperature changes and vibrations. The unintentional emissions are also tested according to DO160. Possible redesigns and final module release with installation manual is done in WP6.

In addition to the technical workpackages, WP1 hosts all management activities that run for the entire duration of the project.



3 Main S & T results

The AirWISE project successfully studied, designed and tested a wireless sensor network node platform for operation in airborne environment and powered by batteries. In parallel a study of energy harvesting potential solutions versus power consumption of this low-power node has been performed. This study gives some future directions of the energy harvesting application for the autonomous wireless sensor nodes.

3.1 Unintentional emissions test

The next paragraphs present measurements of the radiated unintentional emissions of the ZorgWave transceiver module to show its compliance with EMC requirements as defined by the RTCA/DO-160D standard. The measurements presented here cover the emission of (unintentional) spurious signals between 100 MHz and 10 GHz.

The electric field strength at a distance of 1 meter is calculated from the received power in a standard gain antenna. The received power is measured with a HP8563E spectrum analyzer (± 1 dB amplitude error) controlled over HPIB by a LabVIEW program. The resolution bandwidth (RBW) of the spectrum analyzer depends on the measurement frequency. The video bandwidth is chosen equal to the resolution bandwidth. The positive peak detector is used for this measurement and the sweep time is 2 seconds.

The noise floor of the spectrum analyzer is not satisfactory in all bands. In some of the measurements, we added a low noise amplifier (LNA) in front of the spectrum analyzer. The gain is typically 25 dB with a -3 dB bandwidth of 6 GHz. Figure 2 shows the noise floor of the spectrum analyzer preceded by the LNA. The equivalent input noise at the LNA input is 25 dB lower than shown in Figure 4. The overall noise floor n lowered by 20 dB compared to the figures without LNA

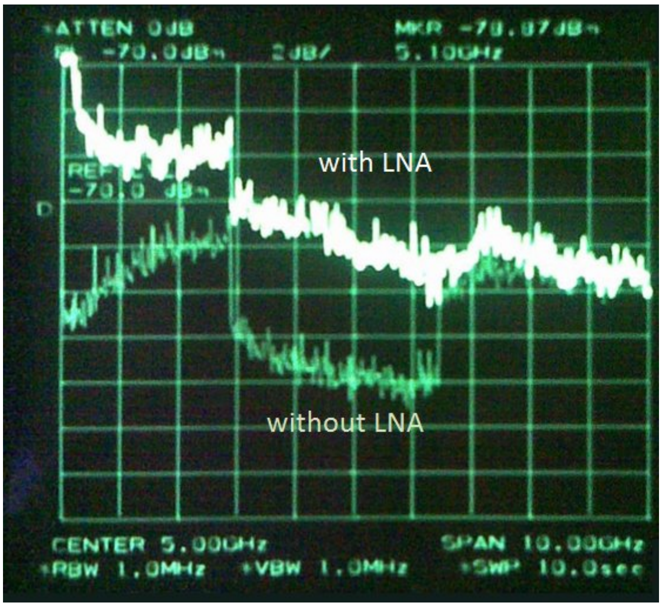


Figure 2: Noise floor versus frequency of spectrum analyzer preceded by LNA.

3.1.1 Spectral mask

DO-160D defines categories in terms of location and separation between the equipment and aircraft radio antennas. As these parameters are widely linked to aircraft type and size, some examples are given with each category definition.

- Category B: This category is intended primarily for equipment where interference should be controlled to tolerable levels.
- Category L: This category is defined for equipment and interconnected wiring located in areas far from apertures of the aircraft (such as windows) and far from radio receivers antenna. This category may be suitable for equipment and

associated interconnecting wiring located in the electronic bay of an aircraft.

- Category M: This category is defined for equipment and interconnected wiring located in areas where apertures are significant and not directly in view of radio receiver's antenna. This category may be suitable for equipment and associated interconnecting wiring located in the passenger cabin or in the cockpit of a transport aircraft.
- Category H: This category is defined for equipment located in areas which are in direct view of radio receiver's antenna. This category is typically applicable for equipment located outside of the aircraft.

We used class H limits which are the most restrictive in terms of EMC radiation. Figure 5 shows the corresponding spectral mask.

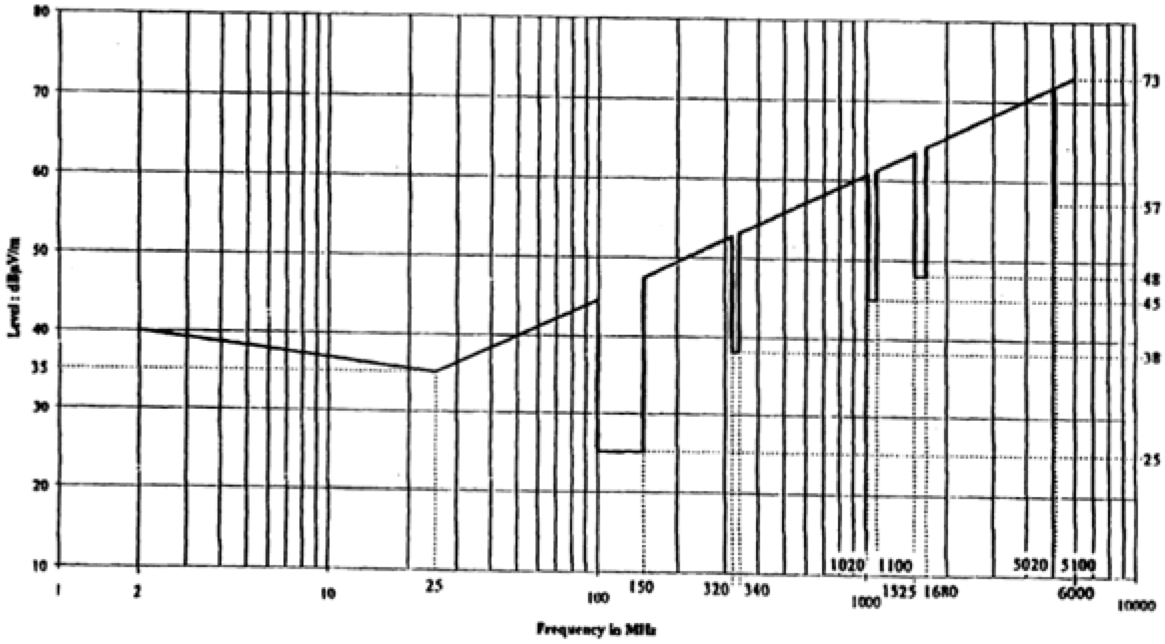


Figure 3: DO-160D class H spurious emissions spectral mask [1].

The distance between the equipment under test (EUT) and the reference antennas was 1 m while the height of both the reference antenna and EUT is 1.2m. The following precautions have been taken:

- Cable insertion losses between the antenna and the spectrum analyzer are taken into account.
- Radiated emissions are measured using both vertical and horizontal polarization.
- Several orientations of the EUT have been checked to find the worst case radiation.
- The module under test was operating in a mode which produces maximum power (continuous mode, radiated power set to the maximum allowed value)

Electric fields strength was measured between 100 MHz and 10 GHz. Figure 6 shows the reference antennas used: A double log periodic dipole array antenna (100 MHz to 1 GHz) and a double ridged waveguide antenna (1 to 10 GHz).

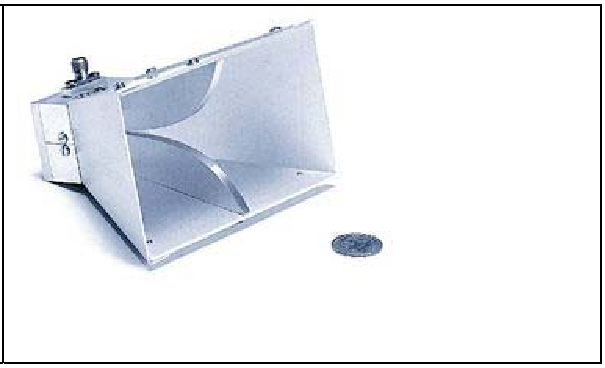


Figure 4: References antennas: LPDA and ridged waveguide horn.

Figure 7 shows the test setup in CSEM anechoic chamber with the double log periodic dipole array antenna and the ZorgWave UT module placed on a tripod.

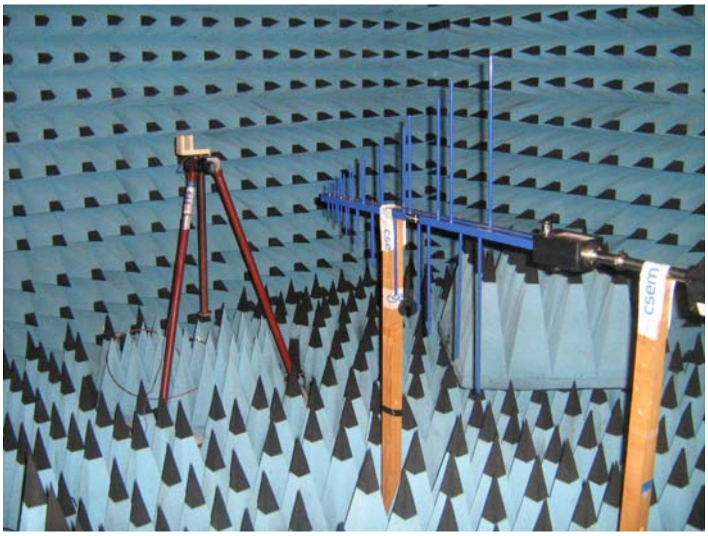


Figure 5: Test setup in the anechoic chamber.

We measured the electric field strength at 1 m distance between 100 MHz and 100 GHz. The measurements above 4000 MHz were performed with the LNA as described in section 2.1. Figure 6 and Figure 7 show the measurement results of the unintentional radiated emission for vertical and horizontal polarizations together with the DO160 class H spectral mask.

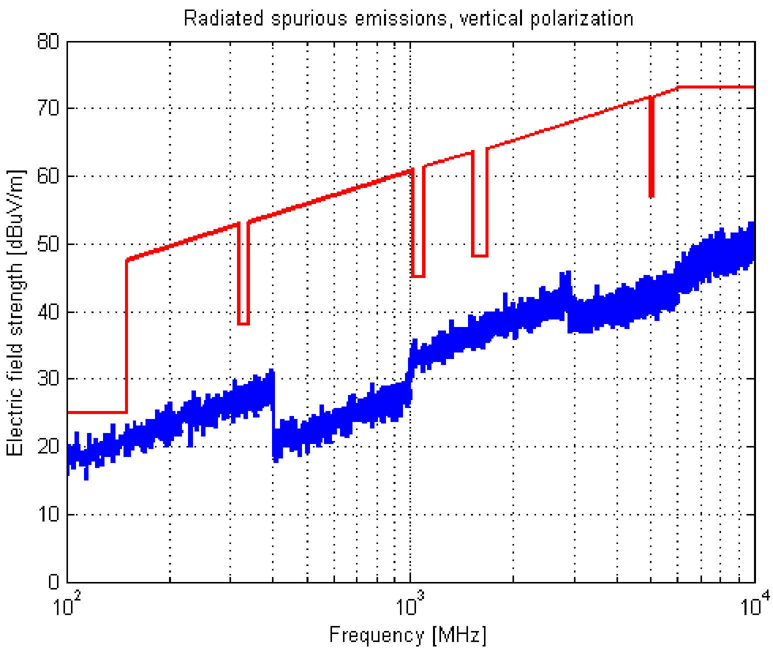


Figure 6: Electric field with vertical polarization.

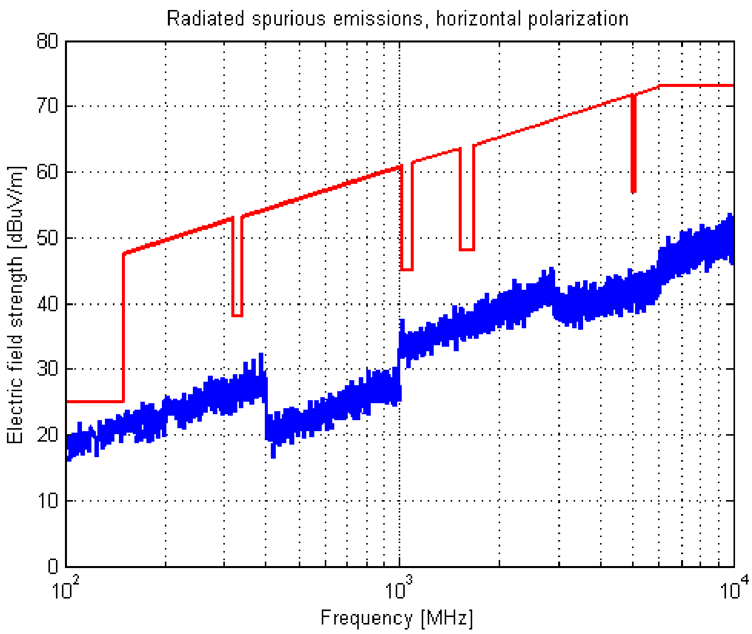


Figure 7: Electric field with horizontal polarization

The results show that the module is clearly compliant with the most demanding DO160 class.

3.2 Vibration tests

The vibration tests have been conducted according to the DO160 standard (DO160F/ED14F, CHAP 8, Category R Curve C1).

For tests, we used a vibrating bowl on which the ZorgWave module was installed. The bowl was controlled by a computer under LabView as shown in Figure 8. The tests were conducted at different vibrating frequencies and accelerations.

Figure 8 - Vibration test setup

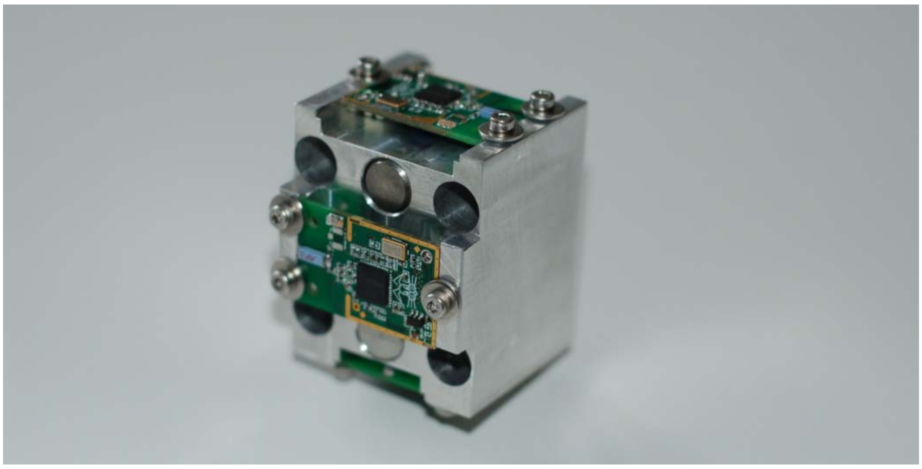


Figure 9 - PCB holder in vibrating pot

As shown on Figure 9, the holding mechanism has been designed to place the module in all 3 axes. 3 modules have been tested three times each. This has been repeated for each axis, x, y, z. During the tests, the ZorgWave modules were not in operations (no communication). After the entire set of vibration tests, the modules were functionally tested as in the case of the temperature tests.

The frequency was varied from 40 to 2000 Hz with a step of 10 Hz. The acceleration was 10g. All 5 ZorgWave modules were functional after the vibration tests.

The tests were later repeated on the AirWISE nodes with success. All nodes were operating after the test.

3.3 Temperature measurements

The following equipment has been used.

- Temptronic X-stream 4310 Thermal Inducing System.
- Apple Macbook running the test front-end SW (st.tcl)
- USB interface card for the ZorgWave module
- 2 ZorgWave modules

Tests were conducted indirectly looking at any alteration in the transmission between 2 nodes, a transmitter and a receiver. All tests are performed by programming the transmitter to send packet for a given duration. Packets are numbered and the receiver can check the number of packets correctly received. The ratio of the missed packets over the transmitted packets is a clear indicator of the success of the test. If the ratio does not increase when temperature is varied from the room temperature to the limit temperatures, this indicates the capability of the module to operate within the required range.

Tests using module powering through USB were not conclusive. This was explained by the USB to serial adapter used for the tests. Some of its components were highly sensitive to temperature. We thus decided to use an external source of energy that was not subject to temperature changes. The resulting configuration is shown in Figure 10 with the test computer, 2 modules, the external power supply and the arm of the x-stream 4310. Nodes were spaced by 1.5m.

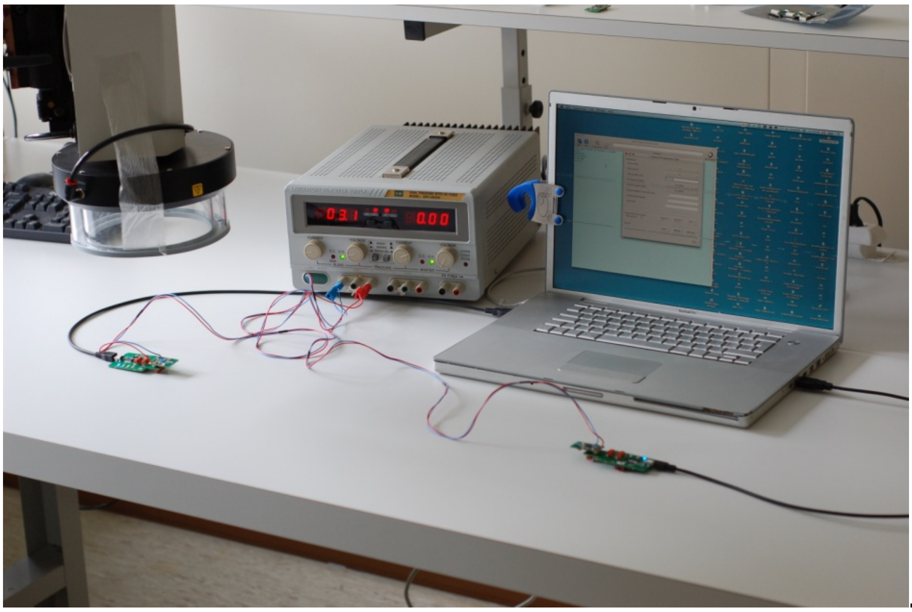


Figure 10 - Configuration 4 : 2 ZorgWave modules, one as transmitter, one as a receiver, both connected to the computer using USB. Module power supply is not provided by USB but using an external power supply.

The tests have been conducted for the entire temperature range from -55 to 85°C over all 802.15.4 channels. Table 1 below shows the results for one of the channels (channel 19). The operations were not affected by the temperature changes (no transmission error).

Table 1 - Measurement results under configuration 4 (external power supply). The same measurements were repeated 4 times without any significant changes.

Tx ID	Rx ID	Temp. °C	Nb. packet send	Missing acks	test duration	dBm	Freq. MHz	Nb bytes	Period ms
3	2	-55	7200	0	30min	0	2445	22	250
3	2	-20	7200	0	30min	0	2445	22	250
3	2	0	7200	0	30min	0	2445	22	250
3	2	25	7200	0	30min	0	2445	22	250
3	2	40	7200	0	30min	0	2445	22	250
3	2	85	7200	0	30min	0	2445	22	250
1	2	-55	7200	0	30min	0	2445	22	250
1	2	-20	7200	0	30min	0	2445	22	250
1	2	0	7200	0	30min	0	2445	22	250
1	2	25	7200	0	30min	0	2445	22	250
1	2	40	7200	0	30min	0	2445	22	250
1	2	85	7200	0	30min	0	2445	22	250

Note that the same tests were repeated on the final module with the same results.

3.4 Current consumption tests

Given the requirements to operate over 18 months on batteries or longer on alternative energy source, it was interesting to measure the real energy consumption of the module in the different operating modes, processor and radio halted, processor running, processor running while radio is halted, processor running with radio in receive or transmit. In principle, it is possible to operate with the processor in halt mode while the radio is in receiving or transmitting mode. As this case happens very infrequently, it was not measured.

To match the software events with the mode changes, we connected 4 pins of the microcontroller to the analyser (MSO7014A Mixed Signal Oscilloscope: 100 MHz, 4 analog plus 16 digital channels). Figure 11 show the setup used for the measurements. The schematics show that the current is measured through a voltage difference (V1-V2) via a 10 Ω resistor in series.

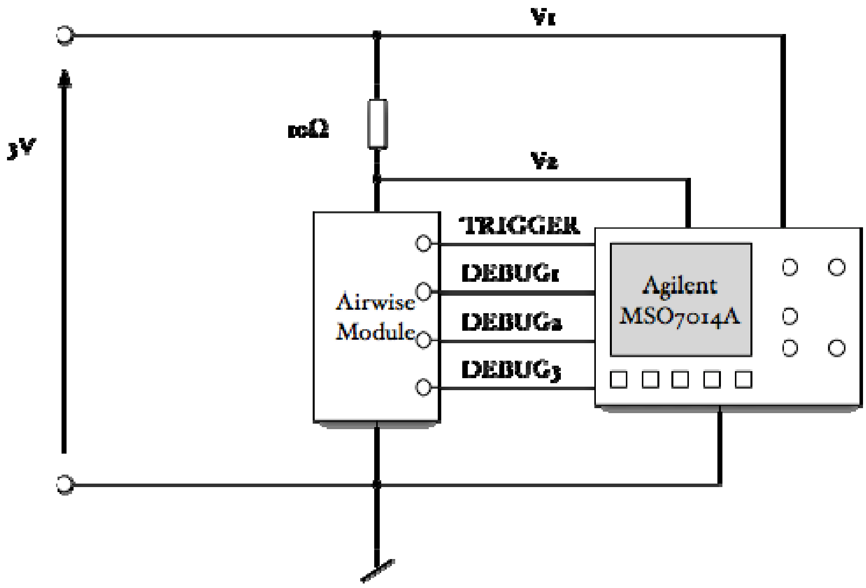


Figure 11 - Current consumption measurement schematics

The ZorgWave module draws the following currents:

- Processor and radio halted (LPM3): 45 µA. This is higher that TI specifies (2µA). However, given the discrete components, it can be explained.
- Processor running, radio halted: 2.4 mA. This corresponds to the MSP 1611 data sheet (0.5 mA at 1 MHz and 3V) given the operations at 3V and 4 MHz.
- Processor running and radio in reception: 19 mA. The typical receive current specification for the CC2420 is 18.8 mA. The measured value is thus expected.
- Processor running and radio in transmission: 10 mA. The CC2420 is specified at 8.5 mA in emission at -25 dBm. Given the processor consumption, the value is within the expectations.

The AirWISE was also measured with, as expected, the same results.

Over a period of 18 months given as a requirement, the halted current would require around 500mA.h of energy. Using a total battery capacity of 18.5 A.h (Saft LS33600 battery) would allow an average current consumption of 1.55mA which corresponds to a duty cycle of approximately 8%.

Operating on alternative sources permits an average current consumption around 0.1mA. This would be possible of such a module with a duty cycle around 0.5%.

3.5 Energy harvesting and Airwise

Deliverable 3.2 “Energy harvesting assessment & corresponding SW guidelines report” analyses the potential of powering the Airwise module by energy harvesting devices. These devices comprise several components: energy storage (e.g. rechargeable battery), energy management (e.g. chips from Linear Technology) and energy harvester (e.g. Seebeck thermo-electric generator). Three issues must be addressed when using such devices in systems:

- Selection of the power source to be harvested and the corresponding physical phenomenon (e.g. solar light and amorphous solar panel)
- Efficiency of the conversions and stability (e.g. voltage adaptation, battery leakage, etc.)
- Durability over the lifetime of the harvesting device (aging of the component under stress, battery charging cycles, etc.)

Although a lot of developments are going on improving the efficiency of the conversion and electronics, the battery technologies are still facing major issues, especially when used in harsh conditions on aircrafts. A partial answer may be found in supercapacitors, but they are suffering from other limitations. Eventually, the most important aspect in energy harvesting is the quantity of energy that is potentially harvested.

The analysis of traditional energy harvesting principles has shown a low but real potential for powering electronic devices in the aeronautic domain. As expected, the mechanical vibrations, including acoustic show a great potential near the source, but not that much elsewhere. The other large sources of energy are solar light and temperature difference.

- Solar light is almost ubiquitous, which allows for continuous generation during the day or, to some extent, under artificial light. However, the solar panels can be screened from the light sources by object, dust or temporary enclosure. The major issue is that the Airwise systems may be reached by any light (e.g. because they are located inside the fuselage or cabinets, which makes the connection between the, and external solar panel extremely complex.
- Temperature difference between the two sides of the aircraft skin can be of several tens of degrees Celcius. However, ultimately both sides are converging to similar temperatures, which allows for a few tens of minutes of generation, which may be not enough during long intercontinental flights.

As mentioned in paragraph 3.4, consumption depends on the duty cycle that the application can support. Typically, primary energy sources (e.g. non-rechargeable batteries) will provide energy over shorter periods for applications requiring a rather high duty cycle (a few per cents), whereas the energy harvesting devices should allow for much longer lifetime, at the cost of much lower duty cycles (less than one per cent).

As a matter of fact, future systems should converge towards less energy: less energy in terms of consumption will require less energy in terms of provision or production. Smart hardware and software, including protocols and energy management strategies may be optimised to drastically reduce the global consumption and extend the lifetime of the components.

The consequence will be that energy harvesting will become much more applicable in many applications and that chemical batteries may become optional. This would allow for lifetime over ten years. It is however difficult to reduce the consumption under the consumption of the sensing part of the system.

3.6 Design of the Airwise node

Table 2 shows the assessment of compliance of the ZorgWave module to the AirWISE requirements. It shows that the pre-existing module is adequate for all aspects except the antenna and the available signals on the connector to the sensors. On these grounds, the decision was made to reuse all the compliant part and study the alternatives for the remaining aspects.

Concerning the antennas, two basic choices were possible keeping the module size in mind, to design an antenna printed on the module PCB or to use a chip antenna. Using an external antenna was not an option as it would lead to a much larger volume. However, an option would be to add a connector to permit the connection of an external antenna in some cases.

Concerning the power supply, given the requirement to adapt the source to the need and a possible use of energy scavenging, the only solution was to keep the source separated from the AirWISE module. A powering connector was thus added, increasing the flexibility of the platform.

Concerning the connection of the sensors, the two possible options were either to use a single connector to power the module, for debugging and to interface the sensors or to use multiple connectors. In addition, one option was to use for powering and debugging the connector that was already in use on the ZorgWave module. This would permit to reuse the existing USB converters that have the same connector.

Using a single connector for all interfaces would simplify the connection but reduce modularity.

Table 2: ZorgWave Module compliance with the AirWise requirements

AirWise Requirements	Compliance
Frequency transmission band 2.45GHz ±50MHz	Yes. This is the band covered by the CC2420 transceiver.
Antenna printed on the PCB.	No. For size reasons, a chip antenna is preferred.
Compatibility with 802.15.x standard and WSN protocols, particularly ZigBee.	Yes. The IEEE 802.15.4-2003 standard has been implemented on the module; Zigbee being on top of 802.15.4 and without special requirements can operate of the module.
Support for standard WSN OS such as TinyOS	Yes. FreeRTOS, MantisOS and TinyOS have been tested on the HW.
Power supply by an alternate power source or battery replacement at least 18months	Yes. Given the module consumption, operations on a 18.5 A.h battery is possible with a duty cycle of around 8%. Operation of alternate sources is possible with a 0.5% duty cycle.
Small form factor (dimensions 20-30cm^2; and weight 20g for the assembled PCB).	Yes. Actual module (with a chip antenna soldered on the board & with SPI bus for sensor interface) measures only 6cm^2 of PCB and weights 10g in total. Depending on the sensor interface technology, size may have to be slightly increased.
Vibrations according to DO160F/ED14F, CHAP 8, Category R Curve C1	Yes. Modules operating without alterations after tests.
Unintended RF emissions according to DO160F/ED14F, CHAP 21, category H.	Yes. Measurement in continuous emission mode over all channels.
Communications port for proceeding mode (4-8 sensors).	Yes. The ZorgWave module has 6 analog inputs, as well as an SPI bus. More digital IOs and 2 analog outputs are available on the board (but not of the existing connector).
System able to be certified according to FAA regulations	Yes. Being RUAG experts in FAA regulations and certification, they advised CSEM in the requirement assessment phase.

The AirWISE module HW demonstrator will consist of two PCBs. The first PCB is the AirWISE module that contains the electronics and the terminal connections. The second PCB is very simple and holds the battery. The battery may be of different sizes. Using a standard plastic material, one can put a lithium battery of AA size (2200 mA.h) or LR14 size (7200mA.h). Other types can be accommodated by designing another PCB while using the same connector. The advantage of having these two PCBs brings the flexibility of adapting easily the battery support for another power system without having modification of RF module routing. In addition, the RF module can be powered directly from a source other than the battery voltage via the terminals located on it. In detail, the AIRWISE is based on ZorgWave with the following modifications:

- The footprint for quartz 31.250 kHz must accept a 32.768 KHz quartz type MS3V T1R-home Micro Crystal.
- The area for the antenna (free components and routing) is enlarged to 20 x 30 mm.
- The connector for external antenna is replaced (ULF to MMCX).
- A new 12-pin connector is placed to interface with the sensors and also to the HAI datalogger.
- In total 6 I/O (analog or digital selection) is on that connector as indicated in the CfP.
- The existing 36-pin programming connector is kept on the bottom side of the module.

The resulting physical architecture can be seen on Figure 12.

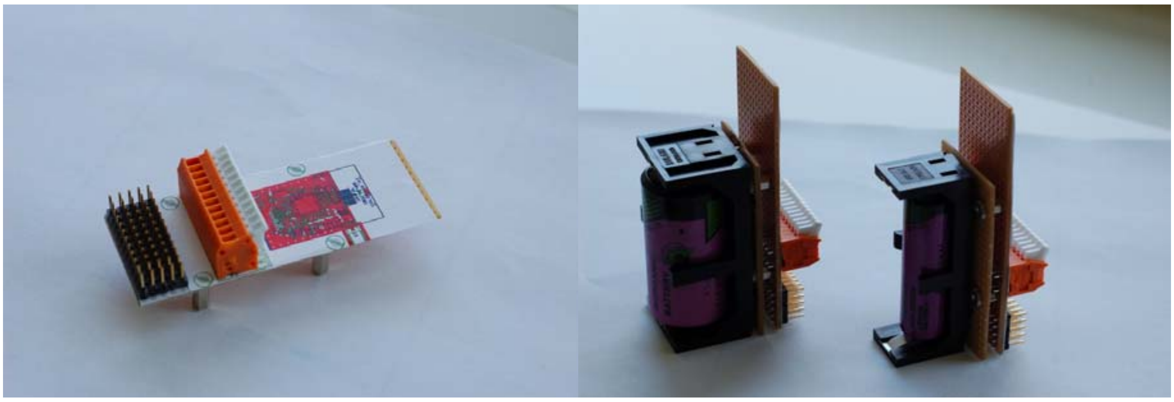


Figure 12: Airwise PCB with battery holder PCB

The resulting design was fabricated, assembled and electrically tested. The manufactured modules were then subjected with success to the same functional tests (communication, temperature, vibration and unintended emissions) as the ZorgWave module. TinyOS was also ported to the module and 5 prototypes (as pictured in Figure 13) were delivered to the topic manager for further tests (outside the scope of the AirWISE project).

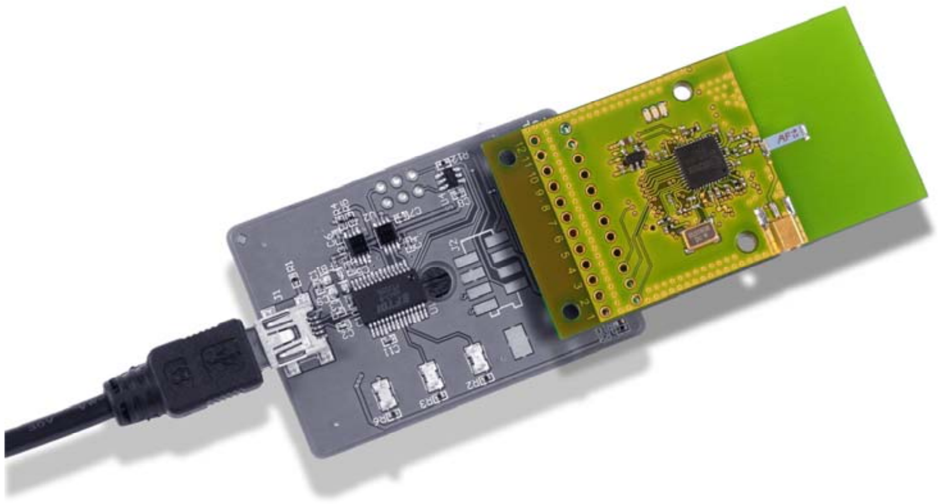


Figure 13 Photo of the AirWISE module/node (green colour PCB).

The results of AirWISE project have been disseminated with a poster at CSEM booth during the ICT 2010 event in Brussels.

4 Potential impact, dissemination and exploitation

The present section discusses the project impact with respect to what was expected when writing the proposal. Then a summary of the dissemination activities follows. Finally, the section concludes with the presentation of the current and future exploitation plan.

4.1 Impact

The final outcome of the AirWise project is the hardware of wireless sensor network nodes for operation in airborne environment and powered by batteries. The AirWise system is a demonstrator that is certifiable and more effort will be needed to bring it into a product certified for commercial aircraft operation. However, the results of this project go in the direction of reduction of weight in aircrafts by replacing cables by wireless sensors networks. It also reduces the cost of maintenance operations since it is easier to replace a node of a WSN than to find the reason of a problem in a cable and replace it.

4.2 Dissemination

Though not formally described in the description of work, the project conducted various dissemination activities. The main event was the participation with a poster at CSEM booth during the ICT 2010 event in Brussels (please refer to the figure 14)

Figure 14 Poster presented at the ICT 2010, Brussels.