CHOSeN

Project Report

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TABLE OF CONTENTS

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1 Executive Summary

The application of wireless sensor network technology in aircrafts and automotive vehicles, for monitoring of supporting structures (system health monitoring) and driver assistance can reduce maintenance costs by a factor of two, as it enables maintenance-on-demand instead of scheduled events, the latter being common practice nowadays. Further on it can reduce accidents caused by technical or human malfunctions due to instantaneous monitoring and response ability and therefore can raise the level of transport safety.

CHOSeN has targeted to develop appropriate wireless communication technology while satisfying stringent reliability and lifetime requirements for these high challenging application scenarios. CHOSeN had strong focus on providing practical solutions for the automotive and the aeronautic application fields, which promise better, more reliable and easier to maintain products in these two of the most significant European industrial domains.

The main improvements are based around an innovative RF transceiver concept comprising a highly reconfigurable RF-frontend and baseband section, a best-in-class Wake-up receiver for lowest power idle channel listening and a tightly coupled protocol processing unit, tailored to MAC-layer tasks to unburden an external, bulky microcontroller from frequent and power-consuming power-up (2 ICs were designed and taped out throughout CHOSeN),. Based on this approach it could be demonstrated, that idle channel listening can be performed at lowest power consumption without duty cycling, suitable for energy autonomous operation, while still retaining sufficient sensitivity margin. To leverage these features on system level, novel MAC layer protocols have been developed (WoR-MAC, BP-MAC) and published.

The development was accompanied by a hardware emulation platform and a system simulation framework, enabling components- and system performance analysis of applications, protocols and underlying physical hardware on architectural, functional and power consumption (respectively energy) level. The system evaluation platform - built around OPNET - also implements channel models for the complex radio propagation in aeronautic and automotive environments, derived from radio channel measurements, which have been carried out in CHOSeN.

The concepts and components developed within the CHOSeN project were evaluated using two representative application scenarios:

The first scenario, provided and evaluated by EADS, addresses the field of system health monitoring of constructive elements by the employment of distributed wireless sensor nodes in aircrafts. Due to the application of ultra low power techniques it was possible to operate the sensor nodes by a harvesting unit, making use of converted thermal energy during climb and descent of the aircraft. For demonstration purpose a mock-up of an aircraft cabin was used.

The second application scenario is provided by CRF and implements a collision warning system by using a variety of different sensors and heterogeneous networks to capture and evaluate vehicle- and environment status information. Data fusion algorithms keep the overall communication traffic at low level and a middleware layer abstracts from the heterogeneity of sensor functions and update rates. This demonstration scenario was installed in a real vehicle.

For both demonstration scenarios real application demonstrators have been built, making use of the CHOSeN developed concepts and HW-and FW-components.

The presence of major European industrial players (EADS, CRF, Infineon) in the consortium will enable rapid commercialization of the project outputs, enhancing European competitiveness in the global transportation market and ultimately leading to new high technology jobs for European workers. It is expected that the involved SMEs (ACCORDE, ARDACO) will increase their revenue thanks to products based on the project results. The technology developed throughout CHOSeN will be able to drive down operational costs and CO2-emissions due to weight-reduction and will contribute to a greener world. Further on it will raise the level of passenger safety. The know-how and new insights gained by the academic and research partners (TUV, TUG, KIT, LETI) will lead to highly skilled next generation students and PhD-candidates.

2 CHOSeN Project Context and Objectives

CHOSeN (www.chosen.eu), while being application-driven, aims at providing scalable and adaptable technologies for wireless sensor network operation thereby allowing the individual sensor nodes to work at operation points which are optimum in their specific, local application context. Therefore the high level objective of CHOSeN is to improve sensor networking operation for sensor nodes with heterogeneous, diverse requirements.
CHOSeN targets to develop appropriate technology, including advanced configurable RF and digital baseband transceiver hardware, networking protocols with scalable Quality of Service in respect of transmission speed, robustness, security, and low-power support, and a generic collaboration middleware that abstracts from the diversity and heterogeneity provided by the layers below, and it will thereby improve the state-of-the-art in system maintenance and driver assistance utilizing heterogeneous wireless sensor technologies. CHOSeN has strong focus on providing practical solutions for the automotive and the aerospace application domain, which promise better, more reliable and easier to maintain products in these two of the most significant European industrial domains.
Both industries are facing a tremendous competition and pressure to develop innovative products, in particular in regard of energy efficiency, environmental sustainability, extended use and added functionality. Added functionality and comfort are mostly driven by added electronics, which brings enormous complexity to vehicles. But this must not end in raised vulnerability or lower vehicle safety, which is an absolute must for dependable systems like automobiles or aircrafts.

CHOSeN integrated technology will help to keep complex systems working safely and to extend their use in minimizing maintenance times and extending life time by making system health monitoring and predictive maintenance feasible. The objective is to use prediction methods to maximize scheduled events and to minimize maintenance incidents. Improving maintenance in the selected applications means a substantial reduction of cost and concurrently advancement in safety by making maintenance more efficient, flexible, secure, more productive and easier by making it more predictable.

CHOSeN technology thus offers new services and applications that are tailored to the harsh environments and the rigid application-specific requirements in two rather disjoint industries, which have until now hindered standardized and proprietary wireless sensor network solutions from being successfully applied in any of these regimes. CHOSeN will create new market opportunities not only in these specific application domains; the application cases serve as reference that the flexibility, adaptability, and extensibility offered by CHOSeN equally well serves other application domains. While seeking stream-lined solutions with respect to communication, inter-operation and system integration are enabled by well designed collaboration middleware, which makes the CHOSeN technology available to a multitude of industrial-size application domains.

2.1 Wireless Sensor Networks Aeronautic Applications

In order to observe and assure the safety, functions and life-time of certain components of aircrafts, a lot of physical data has to be collected, processed and matched with system models. These measurements are related for instance with the temperature impact over time on different critical parts, the pressure, distension and torsion of parts of the landing gear and so on. Many of these measurements are done during the maintenance times of aircrafts; parts are disassembled, audited and possibly exchanged. The effort is huge and so are the costs of the maintenance times. So it is obvious that integrated system health monitoring could reduce both the time the airplane is maintained and disassembled as well as the maintenance costs.
It is also obvious that a lot of distributed measuring points with various functions are needed (see Figure 1).

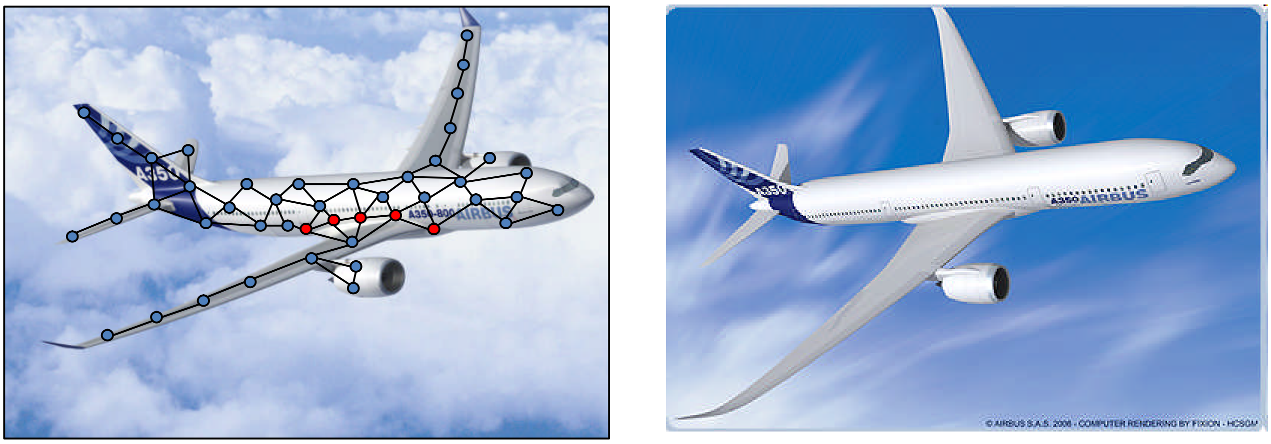


Figure 1: Distributed sensors for system health monitoring in an aircraft

These sensors will have different requirements in terms of power consumption, vibration and shock tolerance, etc. They will also have different capabilities in terms of data priority, data rate, latency and frequency. Some of these sensors could certainly be wired, while others can only be wireless due to their positioning. There are a lot of different aircrafts and aircraft configurations, and the future will certainly bring new maintenance models demanding more measurement points and/or other physical input. Therefore, it is desired to have a general communication infrastructure, including the sensor nodes, communication protocols and data collecting and presentation platform. A common platform for all types of sensors does also have additional advantages:

- only one type of hardware to test and verify
- easy design of new sensor components
- low-cost because of high number of units
- flexibility and scalability

The general sensor node design and communication platform would even allow using the same base system for structure health monitoring in other industrial fields.

2.2 Wireless Sensor Networks for Automotive

In the automotive environment, sensors and actuators along with communication nodes have to fulfil the following main requirements:

- Low cost
- Low power consumption
- High robustness
- High reliability

The approach of utilising WSN technology to achieve such characteristics in a scalable way (i.e. keeping up with the increasing number of network nodes) seems to be promising for the following reasons:

- The use of wireless sensors has a non negligible impact on the reduction of the amount of in-vehicle wires and thus on costs, due to materials, to fitting up and finally to maintenance.
- For the same reason, the extra-cost due to the increase of nodes is much less than the one required for standard wired technologies.
- The long-term challenge of wireless energy transfer or local energy scavenging gives the perspective of completely wireless networks (both data and power).

Figure 2 shows, from a strategic perspective, the different levels of integration of wireless sensor networks technology into the vehicle system: from porting of existing sensors from wired to wireless (relieving the wired network from saturation condition) to the extensions of wireless networks to allow novel, more flexible applications, as well as the improvement of existing ones.

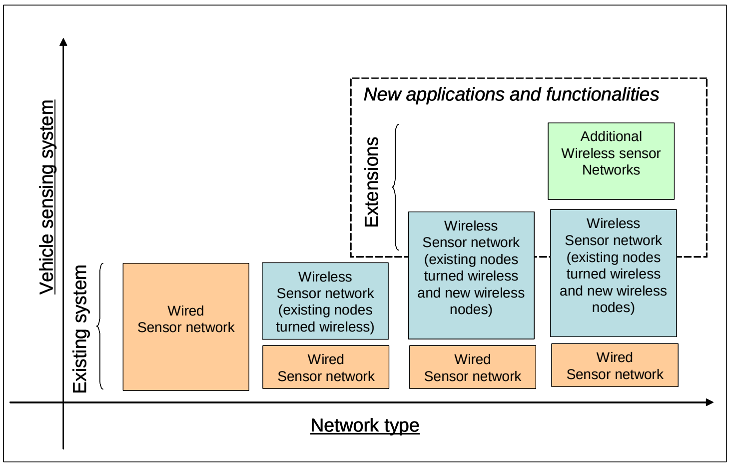


Figure 2: In-vehicle sensor networks

As an example, the dead reckoning system for navigation can be cited. This system is used for vehicle localisation and compensates the absence of GNSS sensor signals in tunnels or covered places, by fusing of GNSS sensors and odometer data. One source of error on odometer measurement is the tyre effective diameter, which depends on tyre pressure. By integrating pressure sensors in the tyre and collecting the data through a wireless connection, odometer data can be corrected taking the effective wheel diameter into account. Another example is a collision warning system, which can calculate the braking distance the more accurate the more information about environmental conditions and vehicle parameters are available (Figure 3).

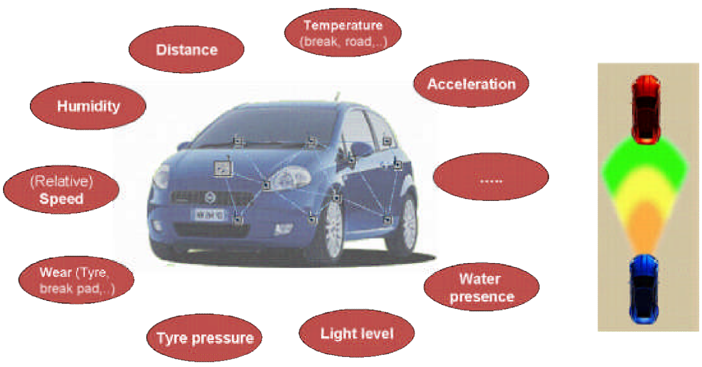


Figure 3: Example of an intra-vehicle network including sensor-parameters for a collision warning system

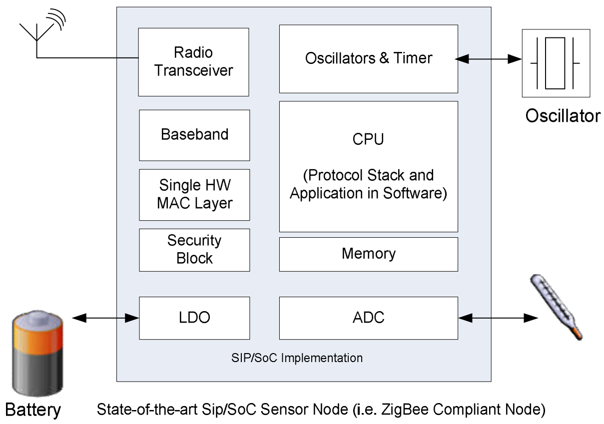
2.3 Scientific & technical objectives

After showing the potential wireless sensor networks offer for the considered applications, in the following the respective scientific and technical objectives are displayed, and the necessary technology framework which will realise these objectives is briefly sketched. The scientific and technical objective of the project is the development and realisation of market conform, wireless network topology adaptive and data per energy optimising communication devices, including an advanced configurable RF and digital baseband transceiver platform, scalable networking protocols with improved QoS in respect of low-power scheduling medium-access control, flexible and reliable routing, and a generic collaboration middleware layer to plug in all type of sensors for system health monitoring.

The adaptable smart wireless transceiver platform aims at significantly improving the major shortcomings of current WSN architectures. This is needed to bridge the existing gap between platform abilities and application-requirements in terms of:

- Energy autonomy
- Reliability and robustness of communication
- Flexibility
- Responsiveness

Due to the nature of WSNs with its inherent sensing, processing and communicating abilities, sensor nodes are highly heterogeneous SoCs or SiPs with a variety of tightly interacting HW/SW-, digital, analogue/mixed signal and radio frequency (RF) sub-systems. A state of the art ZigBee-type node is shown in Figure 4.



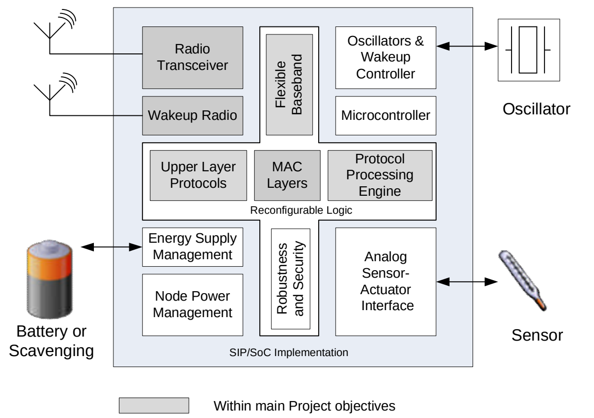


Figure 4: State-of-the-art sensor node

Figure 5: ***CHOSeN*** **enabled sensor node**

With the results of the *CHOSeN* project, the integrated sensor node will provide significantly more flexibility, see Figure 5: In gray, the blocks are highlighted which are within the main project objectives and where significant progress beyond state of the art is being expected. Compared to the state-of-the-art ZigBee-like of Figure 4 nodes, for which a monolithic protocol is implemented on a microcontroller (besides MAC which is partly in hardware), the envisioned platform shown in Figure 5 exhibits scalable and flexible dedicated functional blocks covering an entire class of targeted applications.
To summarize, the scientific/technological development goals of the CHOSeN project comprise:

- <u>OBJECTIVE 1:</u>
  Generic Advanced RF Transceiver Platform
- <u>OBJECTIVE 2:</u>
  Middleware architecture that copes with the heterogeneity of the different network and application requirements, particularly for QoS
- <u>OBJECTIVE 3:</u>
  Low Power Scalable Protocol Processing Engine
- <u>OBJECTIVE 4</u>:
  Validation in highly challenging application environments

3 S&T Results

3.1 Introduction – Technical Approach

Figure 6 schematically depicts the technical approach of CHOSeN. Based on the CHOSeN contributing partners' focus fields and know-how, a full vertical value chain was addressed, starting from chip design on component level up to protocol and application software and demonstrator development on system- and application level. Due to the envisaged support of sensor functions with heterogeneous properties in terms of update rates, latencies, responsiveness, etc., scalable QoS needs to be supported by the components.

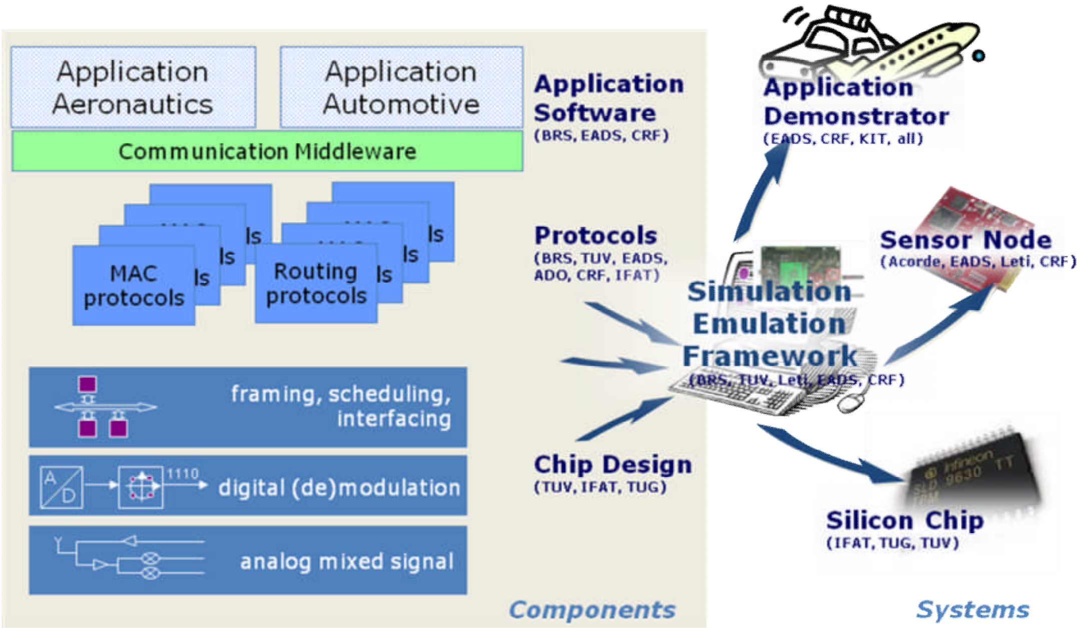


Figure 6: CHOSeN - Technical approach

As efficient synchronization media for partner activities both a simulation-environment (based on OPNET network simulator) and an emulation environment (based on FPGA prototyping; mainly for ASIC-prototyping of the Smart Transceiver, comprising the RF frontend and protocol processing unit, and Wake-up receiver, see Figure 7) has been setup. Physical key parameters, examined by the FPGA platform and later by characterization of the smart transceiver and wake-up receiver ASICs on component level, have been identified, captured and fed by means of abstracted models into the simulation environment for system level analysis. Together with protocol, middleware and application models (including RF-channel models), implemented upon the OPNET-simulation environment overall performance simulations were carried out, thereby guiding HW-development activities to carry out optimizations in an effective way and vice versa.

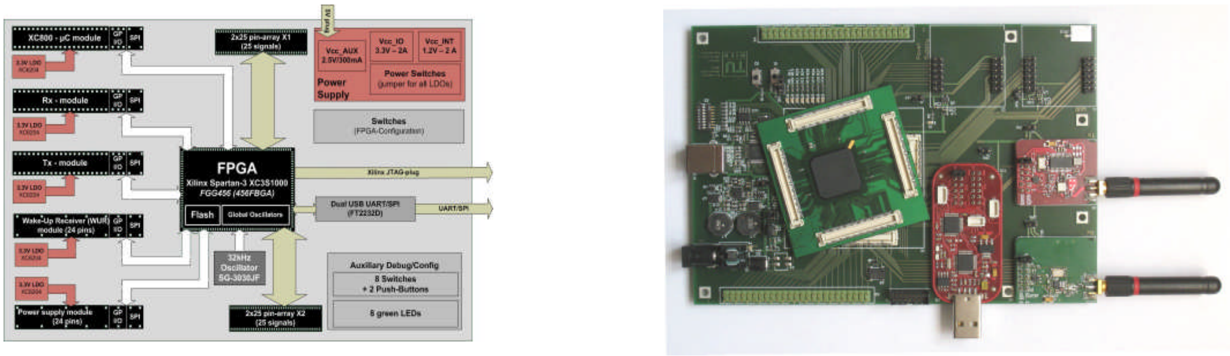


Figure 7 : FPGA based system integration platform

OPNET is a simulator built on top of a discrete event system. It simulates the system behaviour by modelling each event happening in the system and processes it by user-defined processes. It uses a hierarchical strategy to organize all the models to build a whole network. The hierarchy models entities from physical link transceivers, antennas, to CPU running processes to manage queues or running protocols, to devices modelled by nodes with process modules and transceivers, to network model that connects all different kinds of nodes together. As shown in Figure 8 the network model is the highest entity and consists of node models; the node model is the subordinate tier, which consists of processors and built-in transceivers. Then, the lowest tier is the processor model. In the right picture the abstracted system-state diagram of the transceiver used within the OPNET simulation model is shown. The implemented models support simulation of both functional and energetic performance figures.

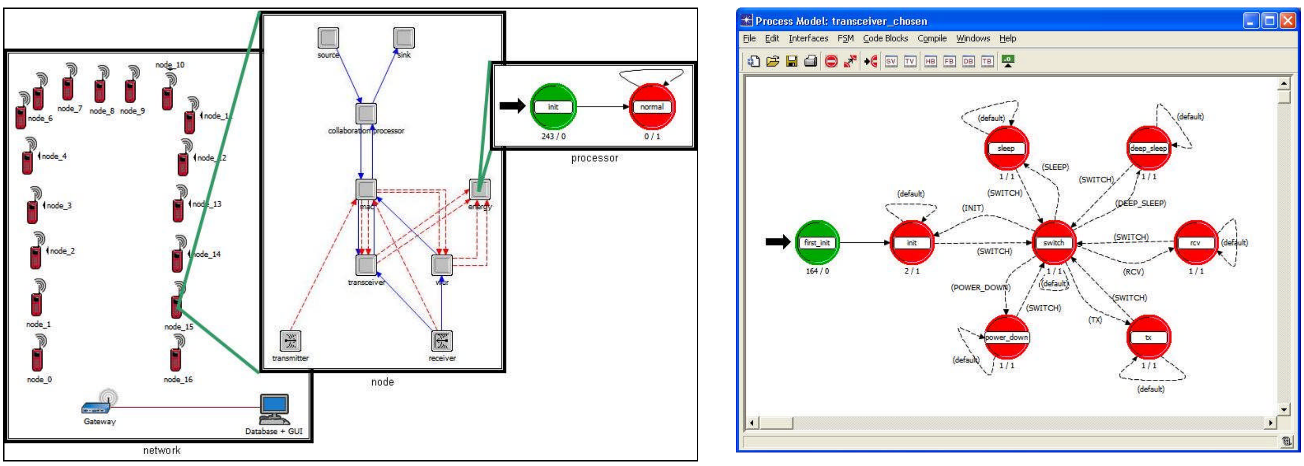


Figure 8 : Hierarchy of OPNET models: network – node – processor (left); RF Transceiver processor representation in OPNET network simulator– system state diagram (right)

The remaining chapters comprehensively describe the results achieved throughout the CHOSeN project. Following key-developments are covered:

- Scalable RF transceiver and Protocol Processor for MAC acceleration tasks
- Wake up receiver
- MAC protocols
- Middleware
- Automotive and aeronautics channel characterization
- CHOSeN HW node and antenna design
- Automotive and aeronautic application demonstrators

- Conclusion

3.2 Scalable RF transceiver and Protocol Processor for MAC acceleration tasks

The developed smart transceiver focuses to optimize power consumption of low-level intensive PHY and MAC operations, while retaining flexibility. In CHOSeN this is supported by

- the execution of PHY/MAC tasks on a lean, tailored HW architecture
- avoiding frequent wake-ups of bulky application controller
- tightly coupled baseband and MAC-acceleration tasks to the RF transceiver frontend - reduced communication overhead for all low-level PHY transceiver operations (direct access to TX/RX bit-stream, configuration of modulation, channels and coding, etc...)
- the introduction of a Protocol Processing Unit (PPU) subsystem
  - Limited HW features to satisfy typical PHY+MAC operations
  - Hardware accelerators for PHY/MAC
  - Adds flexibility
  - Provides fast, dynamic reconfiguration by multi-config preconfiguration
  - Offers high level command interface

A block diagram and a list of important features of the scalable and adaptable baseband transceiver, offering widely autonomous, reconfigurable and adaptable MAC layer operation, are shown in
Figure 9 and listed in Table 1:

Feature	Comment
Start of frame detection	Allows packet-oriented and autonomous (low-power) operation very short run-in and multiple formats supported
Line encodings	coding gain from bi-phase codes (3dB) should be exploited, tolerance against / detection of code violations
Clear channel assessment, Link quality indication	Necessary for carrier-sense multiple access; "listen-before-talk". LBT will most likely be added to ETSI requirements in the future. Could be based on RSSI threshold.
automatic packet assembly	e.g. copy source address from user-defined register, handle frame length, etc.
Security module (AES)	Allows to secure the privacy of transmitted information and authentication of messages.
CRC check	check for validity of packet when received, a set of CRC modes (8 bit, 16 bit) and checksums (e.g. direct TV) to be supported
Slow Frequency hopping	Allows to transmit a packet following a sequence of channels. The sequence is directly controlled by the TRX autonomously.
Default protocol and frame formats	Allows the transparent "data pipe" like use of the TRX without configuration (but non-optimum).
Multi config	Allows fast and flexible referencing and reconfiguration of prepared configurations.

Table 1: Features of the CHOSeN Smart Transceiver

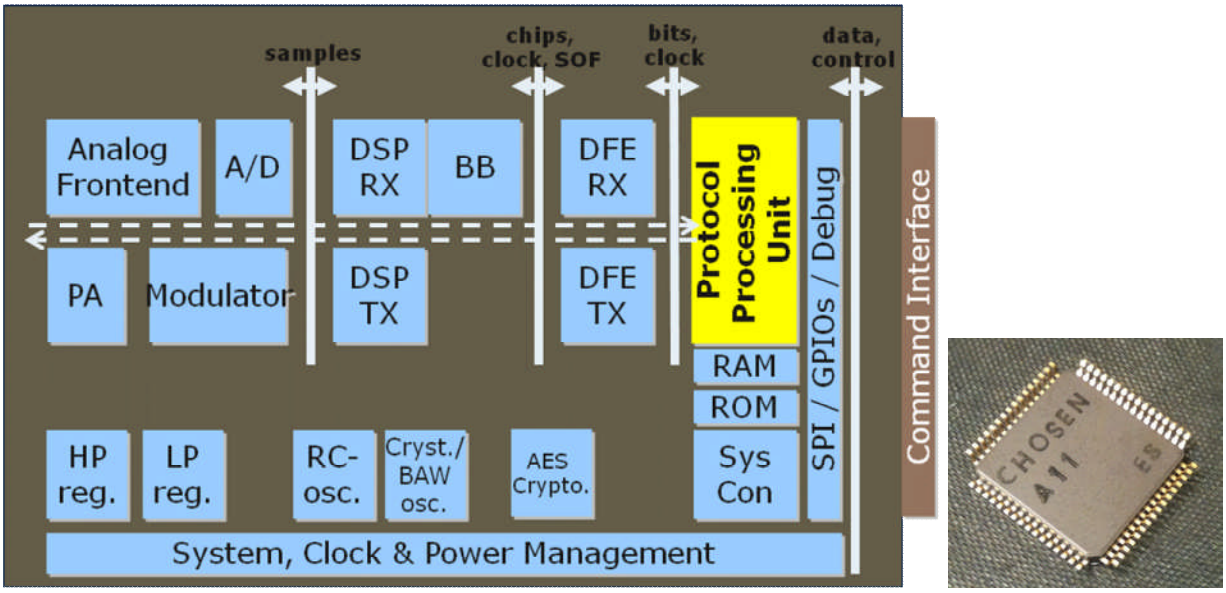


Figure 9: Block diagram of the CHOSeN Smart Transceiver (left) and a photo of the packaged chip prototype (right)

Characterization results of the System-on-chip ASIC developed throughout CHOSeN for key parameters are given in
Table **2**. This table also shows a comparison with other productive (sub-GHz) transceivers, which are available on the market. As can be seen the CHOSeN smart transceiver supports more ISM frequency bands and exhibits an extended temperature range towards higher temperatures, which is crucial and particularly important for the automotive domain. While some key parameters are in similar regions for all listed transceiver chips, the CHOSeN smart transceiver is superior in terms of active power consumption than other ones, despite of the extended temperature range. It shall be noted, that system performance of the CHOSeN smart transceiver with integrated programmable protocol processor shows better or at least similar key figures as the NXP and Semtech transceivers, which have dedicated FSM-based glue logic integrated for the digital processing part, and therefore do only support a fixed set of features. They further only support restricted MAC-layer acceleration functions and rely on a separate external Micro-Controller for complete MAC-layer (and higher) protocol processing purpose. Therefore the benefit of the CHOSeN smart transceiver is even higher when integrated into a WSN-system scenario.

Parameter		Analog Devices ADF7023	TI CC1110Fx	NXP OL2381	Semtech SX1233	Infineon CHOSeN TRX
General	Temperature Range	−40 ... 85 °C	−40 ... 85 °C	-25 ... 85 °C	- 55 ... 85 °C	-40 ... 110°C
	Frequency Bands (MHz)	433/868/915	315/433/868/915	315/433/868/915	315/433/868/915	315/433/868/915/950
	Data rate	1 - 300 kbps	< 500 kbps	< 112 kbps	< 600 kbps FSK	< 112 kpbs FSK
	Rx Sensitivity	−116 dBm at 1 kbps, 2FSK	−110 dBm at 1.2 kBaud	-112 dBm at 2.4 kbps	-105 dBm at 38 kbps	- 114 dBm at 10 kbps
Clocks	XOSC	26 MHz	26 MHz	16 MHz	32 MHz	22 MHz
	RTC	32 kHz	32 kHz	16 kHz	62.5 kHz	100 kHz
Current Consumption	Power down	0.15 µA	0.3 µA		< 1 µA	0.24 µA
	Low Power Mode (RTC on, XOSC off, data retention)	1.6 µA	0.5 µA - 220 µA (retention)	1.6 µA	1.2 µA	1.5 µA
	IDLE	1 mA	5 mA	1.2 mA	1.5 mA	1.8 mA
	RX	13.5 mA	19.7 mA @ 1.2 kBaud	16.5 - 21.5 mA	16 mA (4.8 kbps)	12 mA (1kbps)
	TX (10 dBm)	23 mA	36 mA	25 mA	33 mA	24 mA
Timing	XOSC Startup Time	240 µs	250 µs	1 ms	500 µs	1 ms
	Receiver wake-up time with PLL Calibration	235 µs	810 µs	350 µs	1.85 ms (4kbps)	450 µs
	Transmitter wake-up time with PLL Calibration	235 µs	810 µs	300 µs	270 µs (4kbps)	450 µs
Data Processing	Packet Engine	8bit RISC	8051	FSM	FSM	Protocol Processor
	Data Buffer	240 byte	255 byte	transparent	66 byte	128 byte
	Crypto	AES128/192/256	AES128	no	AES128	AES128
	Error Detection/Correction	CRC16	CRC16	no	CRC16	CRC16

Table 2: Comparison of key parameters for different (state-of-the-art) transceivers and the CHOSeN Smart Transceiver

3.3 Wake up receiver

Throughout CHOSeN a Wake up receiver device has been developed. In contrast to state of the art idle channel listing, where duty cycled operation of the main receiver is applied for driving down the average power consumption, within CHOSeN a dedicated ultra low power always-on wake up receiver has been designed as accompanying device of the main receiver with the task to listen to the channel in order to detect a certain wake up pattern. Upon reception of the wake-up pattern the wake up receiver wakes up the main receiver for reception of the data payload packet.

Block diagram

Figure 10 gives an overview of the Wake-Up Receiver ASIC (WuRx). The main building blocks are an RF envelope detector, the low noise amplifier, bandwidth filter and gain stages, and the baseband signal processing unit. The implementation includes an ultra low power mixed signal correlator for improvement of sensitivity and alternatively, an analog to digital conversion block for optional digital correlation via either an ADC by successive approximation principle or pulse with modulation output. The digital signal processing offers enhanced flexibility (implemented within the FPGA only). The only external components required for the WuRx are coils for the matching network and an optional filter to improve the robustness against interference.
The WuRx supports power down mode and power save mode with register content retention and an ultra low-power voltage reference for core voltage regulation. Figure 11 illustrates the behavior of the Mixed Signal Correlation Unit. The Interrupt Request output is asserted as long as the configured sensitivity threshold is exceeded.

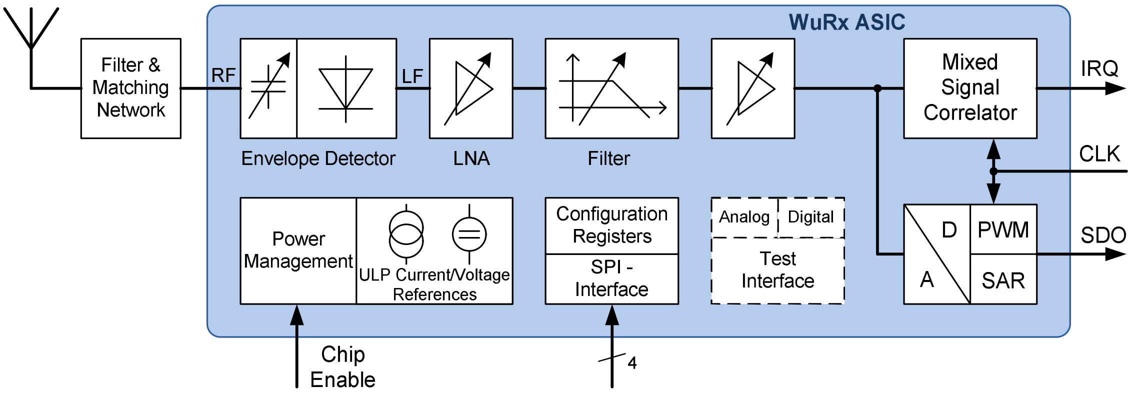


Figure 10: Wake-Up Receiver Block Diagram

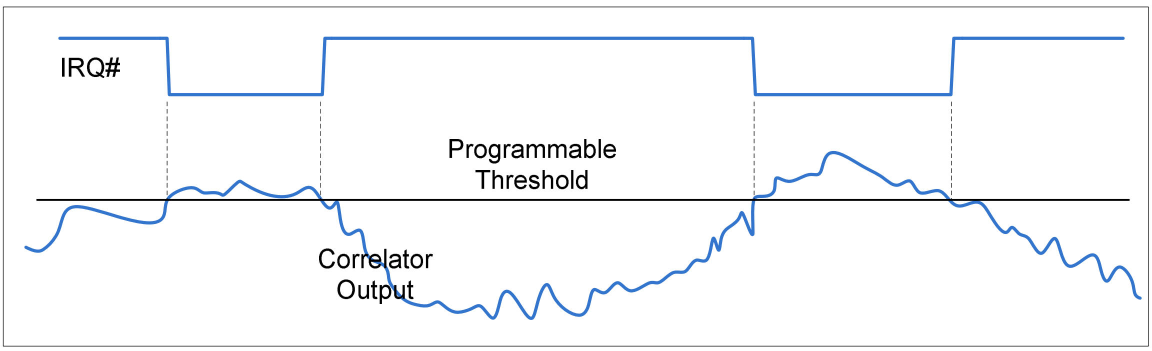


Figure 11: Illustration of Interrupt Request for Mixed Signal Correlation

RF Frontend

The first stage in the RX frontend is a combined low noise RF-detector and amplifier. **Figure 12** shows the equivalent input structure of the input stage containing also the parasitics from bond wire, pads and ESD protection circuits. In receive mode, the input impedance is 0.6 pF in series with some 8 Ω of losses. The two external coils match it to a 50 Ω antenna load at 868 MHz. For compensation of coil tolerance, the equivalent input capacitance can be tuned by ±5 % to adjust center frequency for maximum sensitivity. The optional SAW filter suppresses out-of-band interference caused mainly by 900 MHz GSM.

The built-in switch can be used for noise calibration purposes or together with the matching network, it provides 0.32 dB return loss when closed and supports design of combined matching network for main transceiver and WuRx.

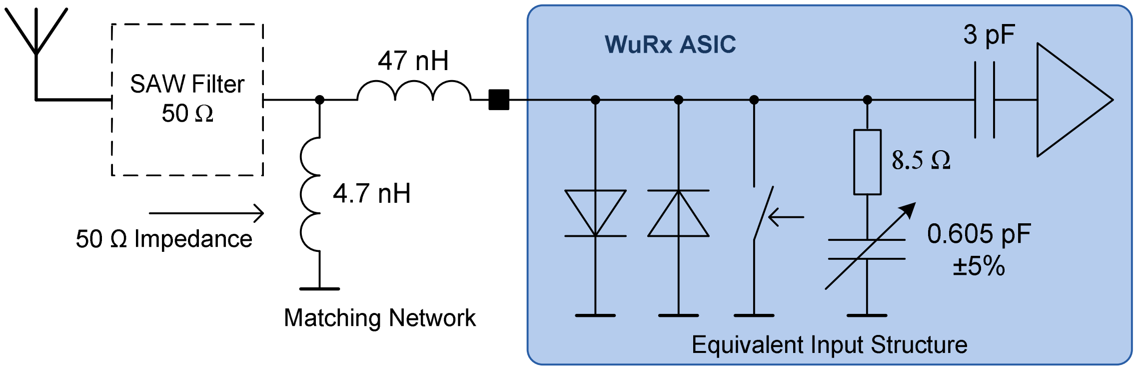


Figure 12: RF Frontend Structure

Key Parameters

Within CHOSeN a chip prototype implementation has been done. Table 3 summarizes the measured characteristics of ASIC samples at room temperature.

Parameter	**Value**	**Conditions**
Receive **Sensitivity**	up to **-70 dBm**	7 ms correlation period with Mixed Signal Correlator, 100 kb/s OOK modulation, SAW filter included (2.2 dB loss)
Data Rate	20 kb/s – 200 kb/s	for Mixed Signal Correlator
Correlation Pattern Length	64 bits	Mixed Signal Correlator
Correlation Period	300 bits / 700 bits	Mixed Signal Correlator Options
RF Input Impedance	8.5 Ω – j318 Ω 118 Ω – j45 Ω	ASIC only at 868 MHz, RF switch off RF switch on
Supply Voltage	1.0 V 1.2 V – 3.6 V	Analog / Digital Core Voltage IO Voltage
Supply Current	1.85 µA 0.4 µA 23 nA **2.3 µA** 12 nA 11 nA	Analog Frontend @ 1.0 V Correlator @ 100 kb/s, 1.0 V Ultra Low-Power 610 mV Reference **Total WuRx** Active @ 1.0 V WuRx Power Save Mode @ 1.0 V WuRx Power Down Mode @ 1.0 V
Power-Up Time	40 ms 70 ms 110 ms	Low Frequency Cutoff Option 1 Low Frequency Cutoff Option 2 Low Frequency Cutoff Option 3
Chip Technology	130 nm CMOS	Automotive compatible

Table 3: WuRx Key Parameter Summary at room temperature

A respective paper "A 2.4µW Wake-up Receiver for Wireless Sensor Nodes with -71dBm Sensitivity" was published at the IEEE International Symposium on Circuits and Systems (ISCAS 2011).

Thanks to low noise implementation and the innovative analogue correlation unit, the realized Wake-up Receiver design beats state-of-the-art receivers by approximately one decade in power consumption for comparable receive sensitivities, as depicted in **Figure 13**:

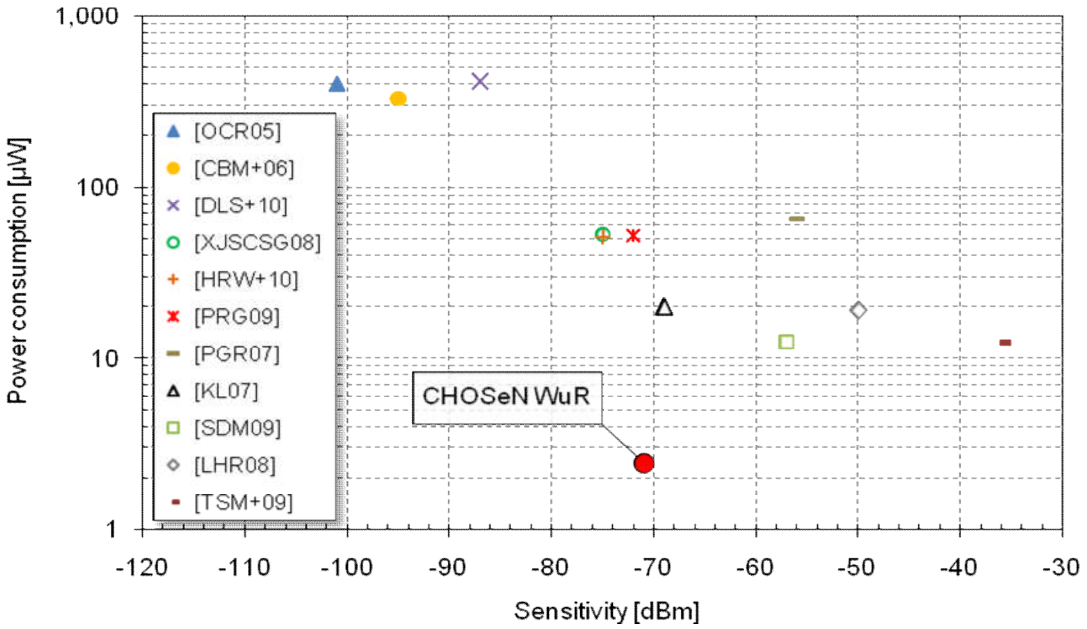


Figure 13: Power consumption versus receive sensitivity of state-of-the-art Wake-up Receivers and the CHOSeN WuR

The comparison shown in the figure was done based on the following publications:

[CBM+06] B. W. Cook, A. Berny, A. Molnar, S. Lanzisera, and K. S. J. Pister, "Low-Power 2.4-GHz Transceiver With Passive RX Front-End and 400-mV Supply," in IEEE Journal of Solid-State Circuits, vol. 41, no. 12, Dec. 2006, pp. 2757-2766.

[DLS+10] S. Drago, D. M. W. Leenaerts, F. Sebastiano, L. J. Breems, K. A. A. Makinwa, and B. Nauta, "A 2.4GHz 830pJ/bit Duty-Cycled Wake-Up Receiver with -82dBm Sensitivity for Crystal-Less Wireless Sensor Nodes," in IEEE International Solid-State Circuits Conference Digest of Technical Papers. ISSCC 2010, Feb. 2010, pp. 224-225.

[HRW+10] X. Huang, S. Rampu, X. Wang, G. Dolmans, and H. de Groot, „A 2.4GHz/915MHz 51µW Wake-Up Receiver with Offset and Noise Suppression," in IEEE International Solid-State Circuits Conference Digest of Technical Papers. ISSCC 2010, Feb. 2010, pp. 222-223.

[LHR08] P. Le-Huy and S. Roy, "Low-Power 2.4GHz Wake-Up Radio for Wireless Sensor Networks," IEEE International Conference on Wireless and Mobile Computing, Networking and Communications. WIMOB 2008, Oct. 2008, pp. 13-18.

[LK07] P. Kolinko and L. Larson, "Passive RF Receiver Design for Wireless Sensor Networks," International Microwave Symposium. IEEE, Jun. 2007, pp. 567-570.

[OCR05] B. Otis, Y. H. Chee, and J. Rabaey, "A 400 W-RX, 1.6mW-TX Super-Regenerative Transceiver for Wireless Sensor Networks," Solid-State Circuits Conference - Digest of Technical Papers, 2005. ISSCC 2005. IEEE International, San Francisco, CA, Feb. 2005, pp. 6-7.

[PRG07] N. Pletcher, S. Gambini, and J. M. Rabaey, "A 65µW, 1.9 GHz RF to Digital Baseband Wakeup Receiver for Wireless Sensor Nodes," in Proc. Custom Integrated Circuits Conference. CICC 2007. IEEE, Sep. 2007, pp. 539-542.

[PRG09] N. Pletcher, J. Rabaey, and S. Gambini, "A 52µW Wake-Up Receiver With -72dBm Sensitivity Using an Uncertain-IF Architecture," in IEEE Journal of Solid-State Circuits. JSSC 2009, vol. 44, no. 1, Jan. 2009, pp. 269-280.

[SDM09] M. Spinola-Durante and S. Mahlknecht, "An Ultra Low Power Wakeup Receiver for Wireless Sensor Nodes," Third International Conference on Sensor Technologies and Applications. SENSORCOMM '09, Athens, Greece, Jun. 2009, pp. 167-170.

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3.4 Automotive and Aeronautic RF Channel Characterization

For mobile communication there exists several channel models for characterizing RF propagation within typical environments, like in-door communication, out-door communication in urban/sub-urban/rural areas, with or without line of sight, etc. Generally in classical indoor/outdoor channel characterization, measurements are performed by defining a spatial grid over which the antenna displaces, or by considering a movement of one antenna with respect to the other. So that channel modelling is always considered as a function of the receiving-transmitting antenna separation.
This approach can be hardly employed for in-vehicle channel measurements, since the manufactures impose some restrictions on the antenna location and the sensors are fixed, no movement of one antenna with respect to the others can be considered. In order to find out effects of RF-propagation in such scenario, important for aeronautic and automotive application fields, measurement campaigns have been carried out at the particular interested ISM-band RF-frequencies. These frequencies are

- for automotive intra-car RF communication: 868 MHz, 2.4 GHz
- for aeronautic intra-airplane RF communication: 868 MHz, 2.6 GHz up to 5.35 GHz

Figure 14 shows the generic setup of the testbed used for all measurements.

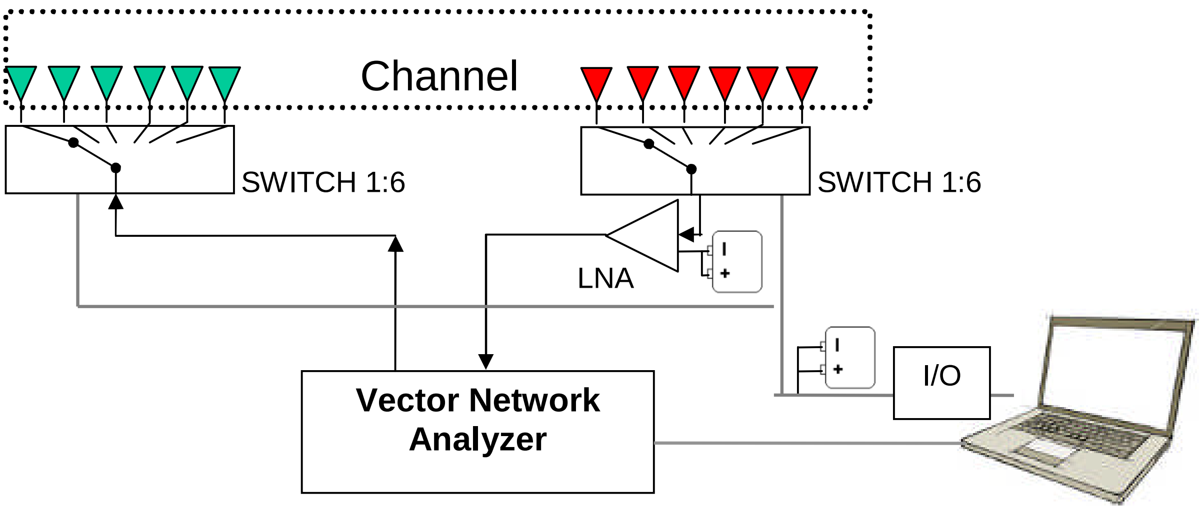

Figure 14: Generic RF channel measurement setup.

Intra-car channel characterization:

For automotive in-car measurements 2 scenarios have been chosen.
A first measurement campaign for automotive applications at 2.4 GHz has been performed at LETI. The frequency step of 2 MHz was chosen small enough to investigate the different sub-bands within the non-licensed ISM bandwidth. As a consequence the measured band is 2-3.1 GHz and the number of measured frequency points is 551. The chosen frequency step allows collecting multipath component coming from a scatterer at distance up to 75 m.
The vehicle employed was a van available at LETI, and nine antenna emplacements have been chosen to investigate.

The antenna emplacements are shown in Figure 15: six of them (Bumper, Driver Side, Mirror and Back side) are put on the external part of the vehicle. These antenna emplacements are somewhat representative of the realistic antenna integration, but this choice allows the investigation of the macroscopic properties of the propagation channel. The Wheel position is located under the wing of the front-left wheel. The Cockpit position is on the dashboard, behind the steering wheel. The Engine position is located at about 30 cm from the front-left wheel.

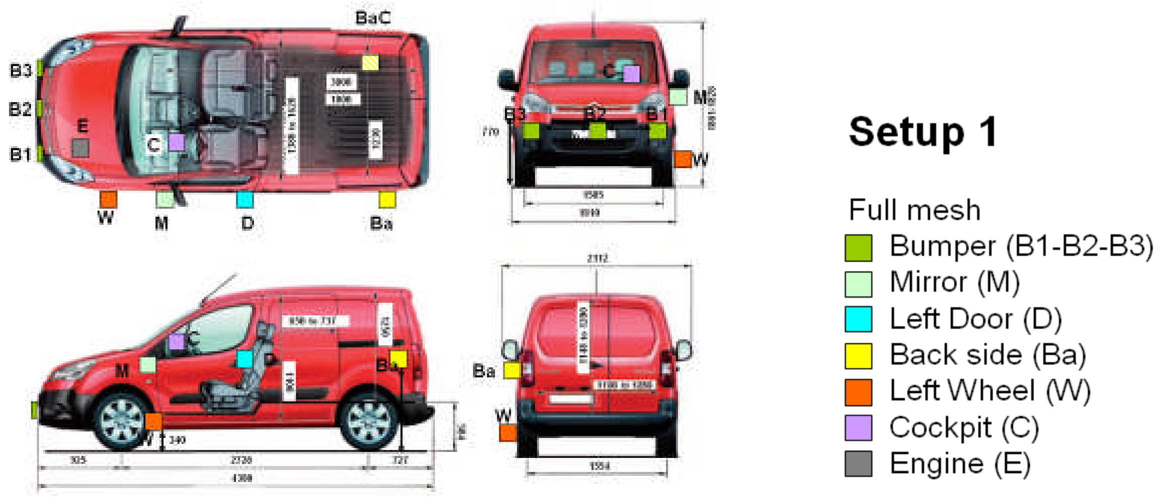

Figure 15: Full mesh characterization setup.

In a second setup measurement three different star WSNs have been tested, in another urban-like scenario. The transmitters are on the central bumper position (B2), in the cockpit (C2) and in the Engine (E) below the cowling. The five receiving antennas are placed as depicted in Figure 16.
In this second setup the car makes a 50 meter round trip by step of two meters. Two different ISM bands have been addressed: the same band around 2.4 GHz as in *Setup 1*, and a second one from 855 to 965 MHz by step of 200 KHz.

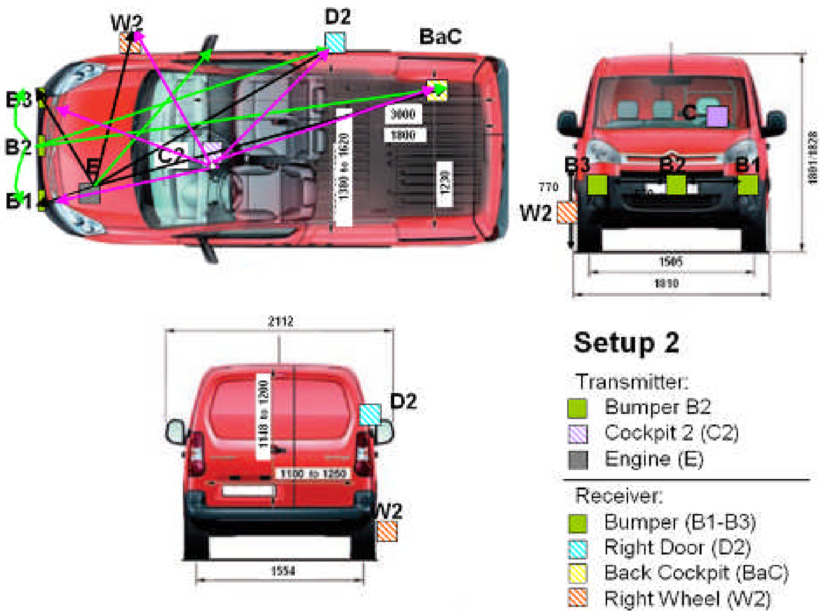

Figure 16: Star network setup

In the following qualitative results of two measurement campaigns for in-car WSNs operating in the ISM bands at 2.4 GHz and 868 MHz are discussed: It has been found, that the antenna orientation, emplacement and surrounding environment have a strong effect on channel characteristics. In particular the in-car channels experience Rice or Rayleigh fading due to off-vehicle scattering objects resulting in multi path combined reception. Moreover multi path propagation combines differently according to the car position. Nevertheless, since the mean path losses measured generally do not exceed the 75 dB, with except of one scenario, IEEE 802.15.4 compliant solutions with a low transmitting level could be employed for these kinds of application.

Intra-airplane channel characterization

Use of wireless communications is expected to extend into the within-aircraft domain in the near future. A number of research groups have been focused in the aircraft channel characterization. Several works have focused on Ultra-Wide Band (UWB) channel. The band around 5 GHz has been investigated as well as the three different bands between 1.5 GHz and 2.45 GHz. Multiple Input Multiple Output (MIMO) solutions have also been addressed.

In these works the antennas are often near the seats, at the same height of a sitting passenger, since the aimed application is for multimedia communication. In CHOSeN, particularly the crack-wire application for structural health monitoring aims the use of wireless node along the ceiling. Moreover the frequencies of interest for the WSNs in the aircraft (i.e. 868 MHz or especially dedicated bands) are not addressed in literature. Therefore measurements took place at 868 MHz and in 2.6-5.35 GHz.

The measurement campaign was carried out in an Airbus A319. Due to the aircraft symmetry, one single side of the aircraft only were considered for the measurements. The TX antennas were placed close to the door, and in the area between the cockpit and the front door, as shown in Figure 17. 6 RX antennas were placed on the ceiling, carried by a mast construction. No glue or tape was used on the aircraft surface.

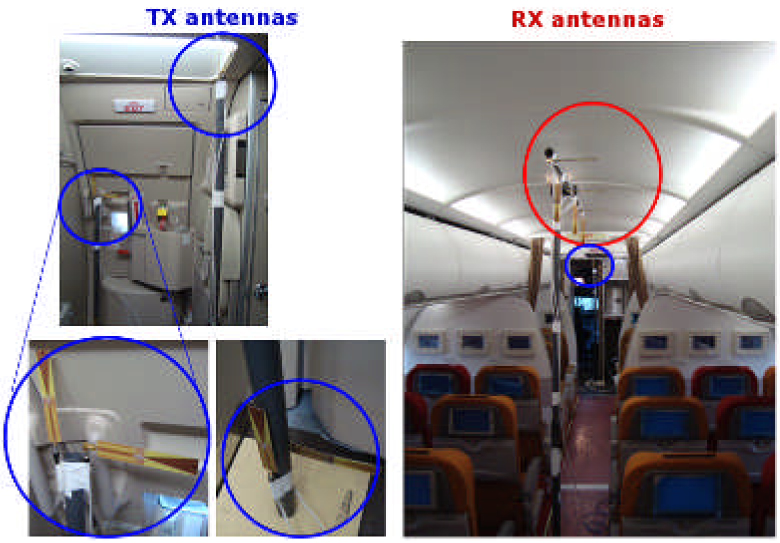

Figure 17: Measurement campaign in Airbus A319

Therefore the measurement campaign addresses the radio channel between the door and the nodes on the ceiling and from the ceiling to ceiling of the cabin. Two different bands have been addressed: 868 MHz and a large band from 2.6 GHz to 5.35 GHz, by employing two different approaches in the channel modelling. The narrow band model for 868 MHz focuses on the fading correlation proprieties and polarization diversity, at transmitter as well as at receiver side. The wide-band channel model between 2.6 GHz and 5.35 GHz is based on a Saleh-Valenzuela wide-band channel description. The results at 868 MHz show that the path loss coefficient is larger than 2, which means that no “tunnel effect” could be verified. In the wide-band model the path loss follows a dual slope with a break point around 1.6 m. The exponential decay of the power delay profile has been also given as a function of the TX-RX separation, in order to model the increasing delay spread along the cabin.

For both automotive and aeronautic, exhaustive measurements series have been recorded and carefully analyzed and evaluated. Examples of model use for the evaluation of the signal-to-interferer ratio have been created and introduced into the OPNET based system modelling framework.

3.5 MAC Protocols and Performance Simulations

For the application scenarios driven throughout CHOSeN protocol solutions must cope with the heterogeneity of QoS-requirements while retaining operation at lowest power level. For that reason MAC layer protocols have been investigated, leveraging the developed RF-transceiver and Wake up receiver HW-components. As a result two MAC protocols, adapted to the complex scenarios, imposed by the automotive and aeronautic applications, have been developed: BP-MAC and Wor-MAC, both have been published at renowned conferences.

BP-MAC

Many Media Access Control (MAC) protocols for Wireless Sensor Networks use variations of the popular Carrier Sense Multiple Access (CSMA) protocol due to its simplicity and its high performance in low traffic scenarios. However, CSMA does not always represent a good choice for WSNs since typical low power transceivers require a significant time to switch between receiving and transmitting and vice versa. Sensor nodes are not able to detect a busy channel during the switching. Thus, the collision probability in WSNs is very high in case of correlated event-driven traffic. Therefore a novel approach has been proposed, called Backoff-Preamble-MAC (BP-MAC) that uses a backoff preamble with variable length in order to mitigate the effect of Clear Channel Assessment (CCA) delay, and increase the overall reliability of the sensor system. The BP-MAC protocol is a highly reliable MAC protocol which uses preambles with variable length to schedule the media access of the nodes. The usage of preambles increases the reliability of the protocol such that more than 98 percent of the packets are received even in high traffic scenarios without using retransmissions while maintaining a low delay. In short form, the BP-Mac is a kind of CSMA/CA scheme, but instead of backing off quietly, it sends back-off preambles to contend for the channel. The node which sends the longest preamble, wins the channel. A detailed protocol description has been made available for publicity and can be found at
http://www.routingprotokolle.de/Routing/Publications/klein_EJSE.pdf
The described medium access mechanism can be used in any MAC protocol to overcome the problem caused by the high CCA delay of low power transceivers for wireless sensor nodes. The results showed that the protocol will take a greater benefit out of next generation low power transceivers compared to CSMA based protocols since its performance is more affected by the CCA delay. Thus, there is great potential that the media access scheme of the BP-MAC protocol will present a more than attractive alternative to the ordinary back-off solution for high reliable WSNs in the near future.
BPMAC has been implemented both in the OPNET based system model and the CHOSeN HW-node.

Wor-MAC

Wor-MAC is MAC-layer protocol, which particularly leverages the dedicated CHOSeN Wake-up receiver approach. The behaviour of the WoR-MAC is detailed in Figure 18, which shows how single addressed wake-up preambles affect a grouped cluster. It also demonstrates how missed preambles are handled by the system where preambles are repeated until a certain threshold is reached and the system continues and begins communication.

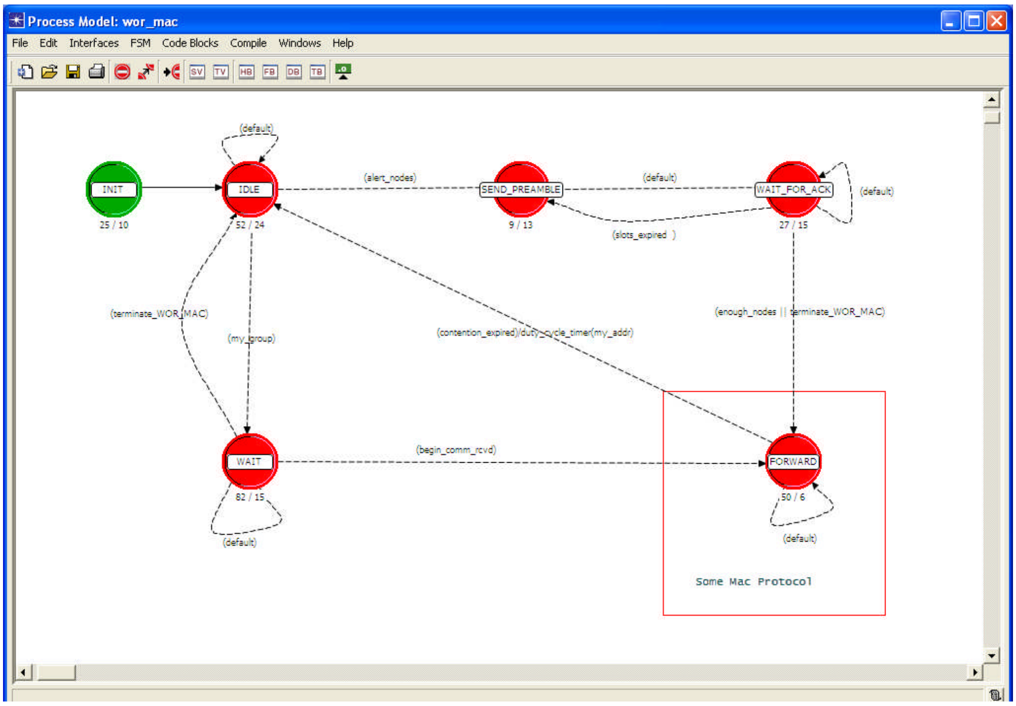

Figure 18: WoR-MAC Process Model from the OPNET Simulation Environment

The protocol has been implemented in the CHOSeN OPNET simulation environment, together with an energy model for the CHOSeN Smart transceiver and wake-up receiver, and on the CHOSeN HW node. A protocol diagram is shown in **Figure 19**.

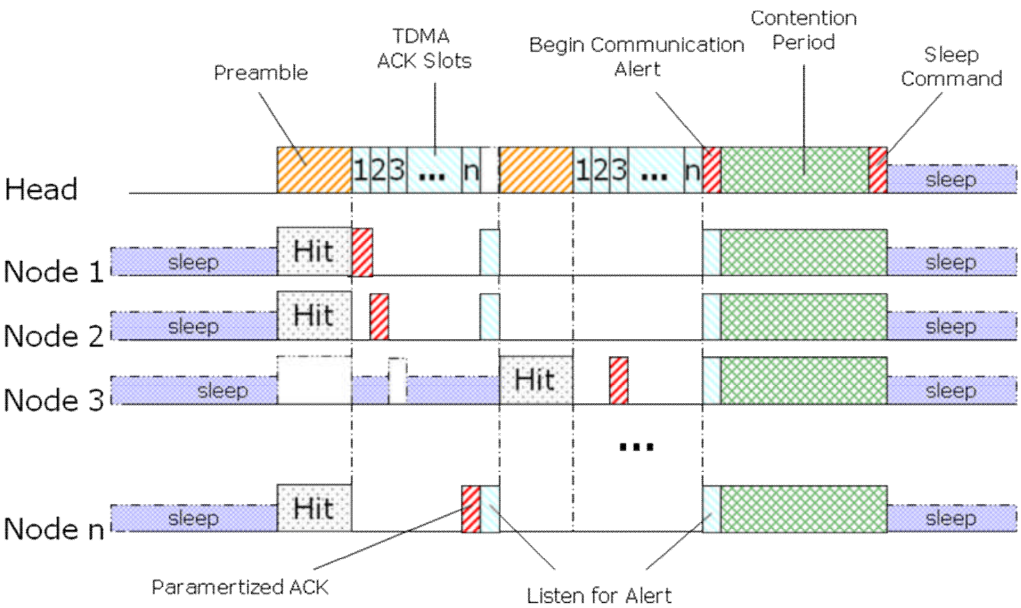

Figure 19: Protocol diagram of WoR-MAC behaviour in a cluster

The performance of WoR-MAC was evaluated using the following metrics as a function of the number of nodes in the network:

Packet Success Ratio The packet success ratio is defined as the number of packets recognized by the receiver on the sink node, divided by the number of packets sent by all nodes in the cluster. The main reason for lost packets is collisions on the channel and noise resulting in bit errors during transmission.

Transmission Delay Transmission delay is defined as the time between the start of the communication period until the packet is received at the sink. This excludes the time, where the packet is stored during the flight and only accounts for the delay added by the protocol. The values shown here are the averages of all packets during a single simulation run with a fixed number of nodes and a specific protocol.

Energy Consumption The energy consumption represents the electrical energy spent by each node during the complete simulated time. Only the power consumed by the transceiver is considered, since the utilization of the other parts of the sensor node is nearly identical for all protocols.

For benchmarking reasons also state-of-the-art MAC-protocols have been implemented in the OPNET framework: X-MAC and IEEE 802.15.4 MAC. The results obtained are as follows (see also Figure 20):

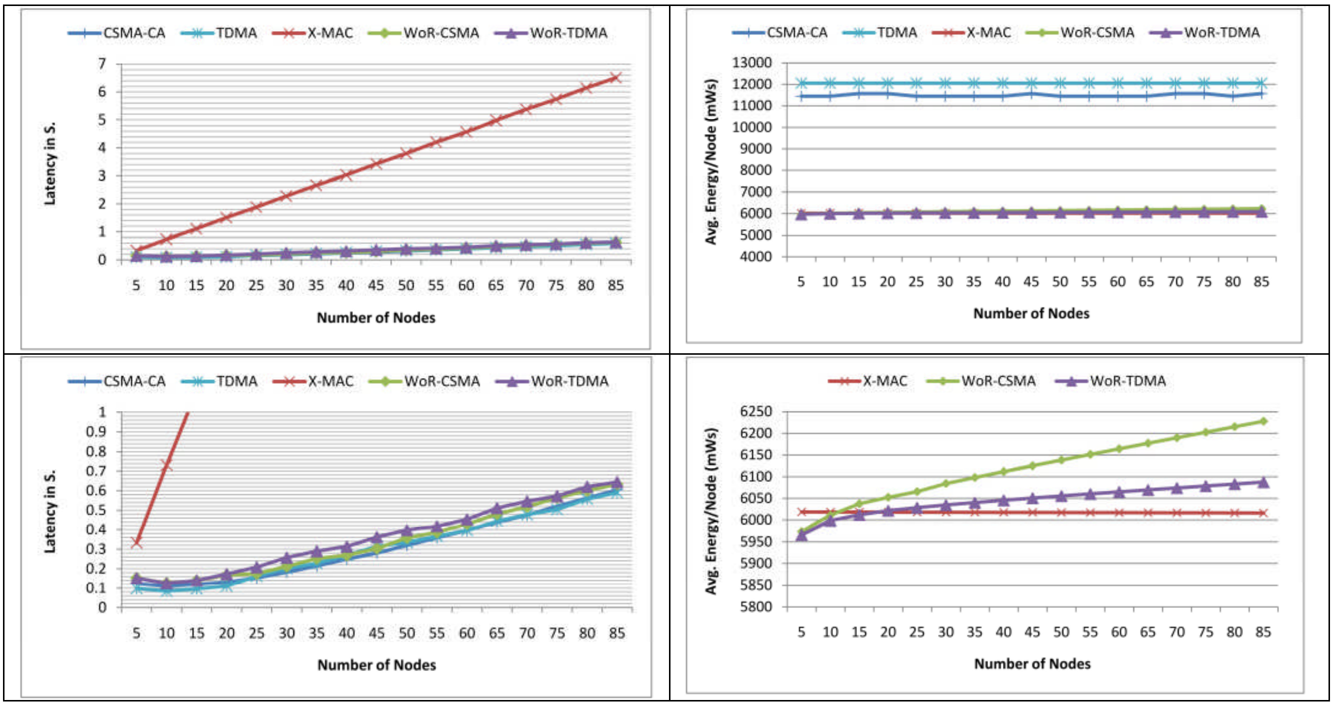

Figure 20: Average latency with respect to the number of nodes (left); Average energy consumed with respect to the number of nodes (right)

TDMA and CSMA-CA consistently incurred the lowest latency. Similarly, WoR-CSMA and WoR-TDMA also performed similarly respectively, maintaining a certain positive latency offset but maintaining the general slope characteristics of the standard protocols. X-MAC on the other hand, performed significantly worse than the other two protocols, with 700 milliseconds of latency for only 5 nodes in the cluster, up to over 6 seconds for large numbers of nodes. This value scaled linearly with respect to the number of nodes in the cluster.

In terms of energy consumption, CSMA-CA maintained a constant power consumption of approximately 11440 mW per node, regardless of how many nodes are in the cluster. The cause of this is simple, since CSMA-CA is not capable of duty-cycling or receiving remote wake-ups, all nodes must remain in listen-mode on the channel. As a result, since the costs for receiving and transmitting data are similar, the amount of energy consumed by a node is not dependent on how many other nodes are in the communication cluster. Similarly to CSMA-CA,

nodes running TDMA must also remain in receive mode constantly as there is no mechanism to duty-cycle while waiting for the beacon. The consumption for TDMA is constant around 12056 mW per node, which is slightly higher than CSMA-CA due to the fact that the nodes remain in transmit mode throughout the duration of their slot period.
X-MAC on the other hand has a far lower energy consumption as each node is awakened asynchronously, transmits its data without contention, and then returns to sleep mode. This consumption behavior is also independent of the number of nodes in the cluster, as each node is able to sleep until it is up to communicate, after which it returns to sleep. Figure 20 (right side) compares the protocols in terms of energy consumption, and then adjusts the scale to detail the three duty-cycled protocols.
WoR-TDMA performs only slightly worse, with an average consumption per node of only 1.2% more than X-MAC for 85 nodes. WoR-CSMA is only slightly worse, climbing linearly to 3.4% greater than that of X-MAC for 85 nodes. It is also interesting to note that both WoR-CSMA and WoR-TDMA consume 0.8% and 0.9% less energy respectively for small amounts of nodes when compared to X-MAC, and WoR-TDMA consumes 0.1% less than X-MAC for 15 nodes. Unlike X-MAC, the consumption of WoR-CSMA and WoR-TDMA is dependent on the number of nodes in the network. This is due to contention during the communication period for one, and the energy required to collaboratively optimizing the contention period using the parameterized ACKs.

Further performance simulations for different automotive and aeronautic applications have been performed throughout the project. Performance evaluation and comparison as well as application scenario feasibility simulations were done and show that the CHOSeN node outperforms state-of-the-art sensor nodes in terms of power consumption in relation to achievable latency and throughput. The developed MAC protocols outperform standard MACs (802.15.4, X-MAC) in the relevant application scenarios. The application scenarios feasibility analysis showed that the CHOSeN hard- and software is well fitted in terms of the defined requirements. Details are available for publicity in the CHOSeN deliverable *D2.2 System Model Definition and Simulation Results* at www.chosen.eu.

3.6 QoS Adaptable CHOSeN Middleware

The middleware solution for the CHOSeN approach is a distributed embedded software/hardware application running on dedicated node extensions. The middleware application is distributed over these middleware nodes, but is also distributed to the wireless sensor nodes where smaller code-portions implement the necessary operations for the middleware.
The middleware nodes interface with the CHOSeN wireless sensor network, as well as the preexisting vehicle communication systems of the respective application. In this fashion they also serve as network bridges within the vehicle, allowing seamless communication between the different modules of the CHOSeN aeronautic and automotive applications. The resulting overall system architecture is shown in Figure 21.
The CHOSeN wireless sensor network is structured in network clusters, where each cluster has a middleware node as its head as also shown in Figure 21. The middleware node informs the cluster about application decisions such as the hazard state of the network. It is also responsible for maintaining the cluster in terms of ensuring that requirements from the application are fulfilled, as well as maintaining redundancy and scalability of the network.
In addition to the middleware platforms, a portion of the middleware is distributed on each sensor node. This allows the middleware to control certain aspects of the network by being able to apply commands received from the central units.

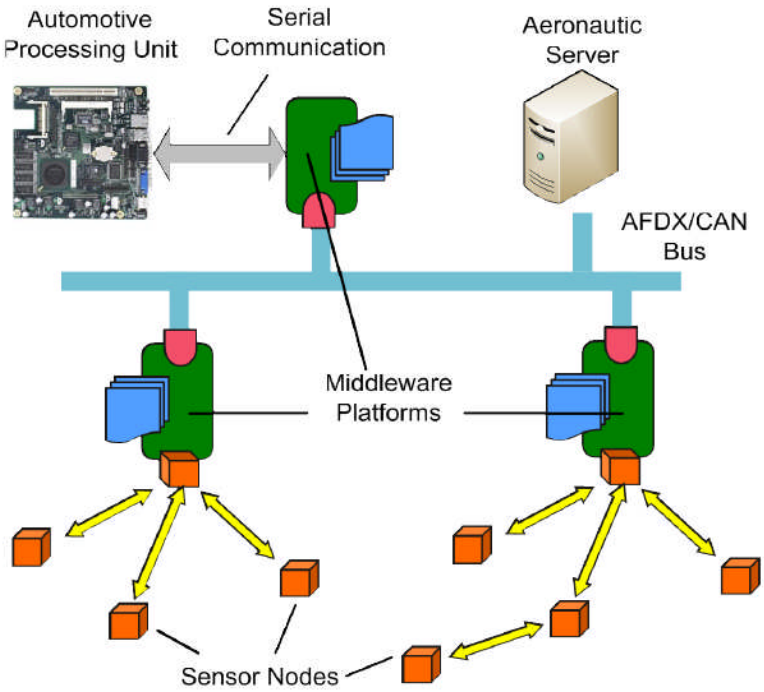

Figure 21: CHOSeN generic system/network architecture with middleware platforms, used for both aeronautic and automotive demonstrator

Figure 22 shows a sketch of the resulting overall networking stack. Figure 22 also considers that depending on the network-position employed, the middleware platform needs to take over different (bridging) roles and has to fulfill different (cross-bridging) tasks.

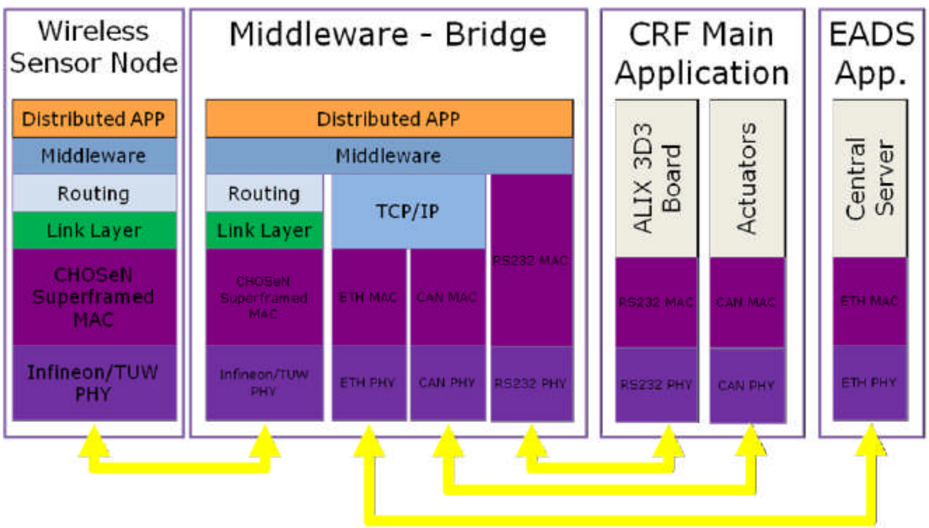

Figure 22: The overall CHOSeN network stack

<u>Communication with pre-existing networks</u>

- **Middleware communication with preexisting automotive network: CAN/LIN**

Controller–area network (CAN or CAN-bus) is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer. CAN is a message based protocol, designed specifically for automotive applications but

now also used in other areas such as industrial automation and medical equipment. The CAN bus may be used in vehicles to connect engine control unit and transmission, or (on a different bus) to connect the door locks, climate control, seat control, etc.
CAN is a multi-master broadcast serial bus standard for connecting electronic control units (ECUs). Each node is able to send and receive messages, but not simultaneously. A message consists primarily of an ID — usually chosen to identify the message-type or sender — and up to eight data bytes. It is transmitted serially onto the bus. This signal pattern is encoded in NRZ and is sensed by all nodes.
The devices that are connected by a CAN network are typically sensors, actuators, and other control devices. These devices are not connected directly to the bus, but through a host processor and a CAN controller. If the bus is free, any node may begin to transmit. If two or more nodes begin sending messages at the same time, the message with the more dominant ID (which has more dominant bits, i.e., zeroes) will overwrite other nodes' less dominant IDs, so that eventually (after this arbitration on the ID) only the dominant message remains and is received by all nodes.

- **Middleware communication with preexisting aeronautic network: CIDS, AFDX**

In today’s aircrafts, a lot of communication interfaces are used, including CAN (ARINC-825), LIN, and ARINC429. However, in the aircraft cabin, where the access points or gateways will be installed, AFDX (Avionics Full-Duplex Switched Ethernet)/ARINC664 and Cabin Intercommunication Data System (CIDS) are most relevant. AFDX is used in the latest aircrafts (e.g. Airbus A380, Boeing 787, Airbus A400M, Airbus A350) and will thus be targeted as the backbone interface for CHOSeN applications. Since AFDX is based on the Ethernet Phy and uses only COTS components, Ethernet is sufficient for the demonstration purposes. Once the wireless sensing technology will be mature enough for product development, the Ethernet interface can be replaced by AFDX. The higher communication layers and the bridging functionality relies on IP communication which will also e supported by the AFDX backbone and thus, the migration to AFDX will be easily possible then.

Communication with the CHOSeN Wireless Sensor Network

As the CHOSeN wireless network is organized in a clustered star topology, all data packets are routed over one of the middleware nodes. This gives a middleware node complete knowledge on all nodes and transmissions in its cluster. Therefore incoming packets can easily be routed according to the destination address. If the recipient is within this cluster, the message will be forwarded. Else the message will be broadcasted on the wired interface to be picked up by another middleware node or
the central application controller. In the other direction, incoming packets from the wired network will be bridged to the wireless network, if the destination address belongs to the managed cluster.

Middleware platform module

The middleware platform module is based on a PIC32MX processor which runs an embedded HTTP webserver. This web server is the communication stack of the middleware platform and drives bus communication over Ethernet or CAN as well as communication with the WSN (see also Figure 22) via a CHOSeN HW node, which includes the CHOSEN Smart Transceiver and Wake-up receiver. The system also has access to a microSD card for application data storage. A photo of the middleware platform is shown in Figure 23.

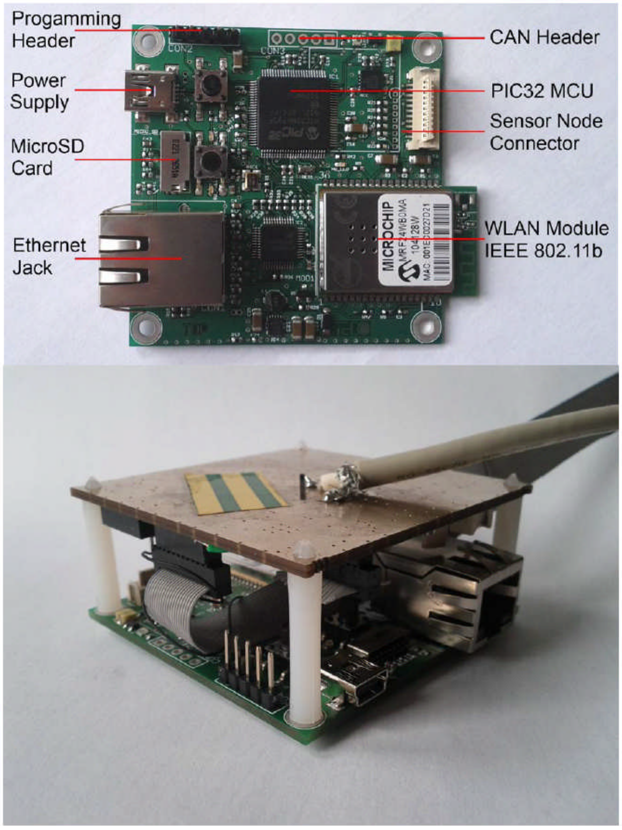

Figure 23: CHOSeN dedicated middleware platform (top), attached to a CHOSEN HW-node (bottom); CHOSeN HW node is shown without mounted antenna

Middleware QoS features

This chapter describes how the CHOSeN middleware handles the QoS requirements of the applications. This is managed based on three requirements that can be defined individually for each application data stream. These are reporting frequency, maximum latency and priority. The middleware uses several approaches to meet these requirements. Firstly, the middleware works macroscopically by using the dynamic switching between multiple MAC protocols to adapt latency vs. power consumption properties of the network based on the current state of the network. The middleware also manages the individual data streams based on the information provided by the application to ensure that each request is fulfilled as far as possible.

- **MAC Protocol Switching**

For the automotive application dynamic switching of MAC protocols is required. The application layer informs the middleware of the current danger level based on advanced analysis of the sensory data done by the data fusion algorithms. This is done using a status message sent from the application to the middleware platform. This information is then distributed to the middleware layer running on all nodes using a status update messages. After this, the middleware effects a change in the MAC protocol used for communication, from WoR-MAC in low-power mode, to CSMA-CA and TDMA in Danger and Warning modes, and back to low-power modes if appropriate. The mapping of each state to a specific MAC protocol is defined during application development.

If specified by the application, the protocol allows defining different reporting frequencies for each of the three states in every subscription message. This is due to the fact that in different situations, not all sensor values need to be polled equally often. The added benefit is that, with a single message, the application can activate faster network settings as well as faster reporting on important data streams.

- **Network Optimization**

As all packets have to pass through the middleware before being delivered to the consumer, meaning the application, and since latency and deadline information is known for each packet, the middleware is always in a position to judge how well the system is meeting requirements. If the system delivers data long before it is needed, then it is wasting energy, where on the other hand if too many deadlines are being missed, then the system needs to reduce latency, even at the cost of elevated consumption levels.
Based on this guideline, the middleware constantly informs the cluster heads within the network about the system performance as a whole. They can then adapt the network parameters of the wireless sensor network to either reduce latency and increase power consumption, or elevate latency levels while saving overall energy. Practically, this is done by reducing the WoR-MAC polling period on the MAC layer. This reduces the amount of time which each node’s transceiver spends in dormant mode, therefore reducing the latency overhead caused by WoR-MAC, but also increasing power consumption.
It is important to note that the system must trust the application not to set unreachable latency goals. If this does occur, the middleware will continually increase power consumption in an attempt to bring latency into an acceptable area. In order to prevent one rogue subscription from terminally affecting power consumption an upper boundary for the set-value is defined per system stated, essentially capping system consumption for each state, thereby also limiting the floor for latency levels (they are an inverse function of power consumption). The application will get informed about missed latency deadlines and the current network state and can adapt its data streams accordingly. Since the system is intended to be configured by a single entity, a cooperative application behavior can be assumed.

- **Subscription Based Optimization**

The second approach used to ensure that the latency and power consumption requirements are met by wireless sensor network is by optimizing the network response on a subscription-by-subscription basis. This involves using the distributed knowledge of the WSN topology as well as of the sensory capabilities of each node within the network. Using this information the middleware can distribute a single subscription over several nodes. This distributes the power consumption for each subscription over several nodes and routes, thus increasing network lifetime. Furthermore it relaxes the data volume over individual routes, which reduces average and maximum latency due to collisions. Practically, this is accomplished using the zone information in the announce messages from each node. A subscription to temperature in zone 1, for example, is equally distributed across all nodes in zone 1 which have published a temperature sensor stream with the ID of the temperature sensor. In this way all nodes within the same zone collaborate to maintain the latency requirements specified by the application subscriptions.

- **Message Queue Ordering**

The middleware handles contention for the medium of different packets based on the associated data stream and subscription information. The principles are based on prioritized message queuing (importance of the sensor, based on mode and class model) and latency (how long the packets have been waiting and how long until they miss their deadlines).
Since the middleware layer handles all data packets from the application layer, as well as packets that need to be rerouted – in the wireless network or from the wired network – it can rearrange the order in which they are forwarded to the MAC layer. The difference between the latency allowable for the measurement as specified by the subscription and the amount of latency accrued is multiplied by the priority for that subscription to form a simple metric for judging message exigency. If a backlog occurs due to low network performance, these values are calculated for each message within the multiple middleware packets accrued, and the messages are sorted into new middleware

packets, ordered by this value. These values are recalculated after each packet is transmitted to ensure that there is no starvation.

3.7 Automotive and aeronautic application demonstrators

For the integration into application demonstrators, a generic wireless sensor HW-node has been designed, making use of the developed CHOSeN components, described in the foregoing chapters. Figure 24 shows a photo of the assembled CHOSeN node.

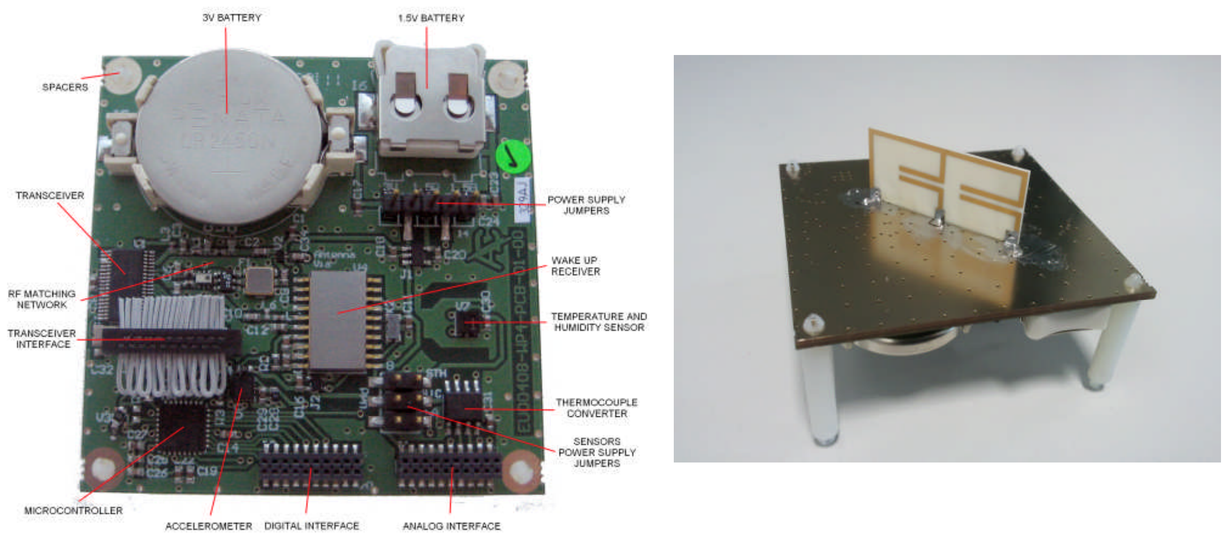

Figure 24: Assembled CHOSeN node (left: top view/component side; right: bottom view/Antenna)

In CHOSeN the antenna shown in the figure has been specially designed to match the requirements imposed by the targeted applications, particularly the installation of nodes in environments with massive metallic surroundings is critical. Therefore the antenna has been optimized for insensitivity against resonance frequency detuning, while still retaining high radiation efficiency. Basic requirements are given in the following table:

Radio characteristic	Objective
Frequency band	ISM 868-870MHz
Maximum reflection coefficient	-10dB
Minimum radiation efficiency	-4.5dB
Antenna maximum dimension	6cm×6cm×2cm

The antenna has been exhaustively characterized, including sensitivity analysis with metallic parts in the vicinity. A radiation pattern 3d-plot is shown in Figure 25. The antenna fully meets the requirements.

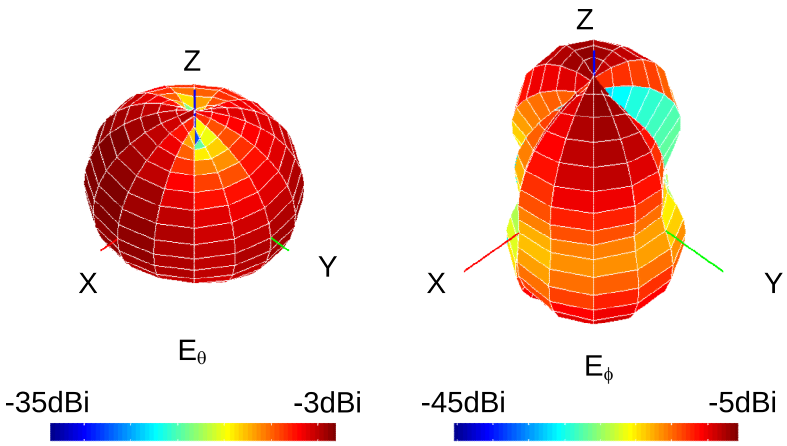

Figure 25: Antenna gain pattern dBi from measurement

A matching network has been designed that connects the antenna optimally to the Smart Transceiver and Wake-up receiver.
More details can be found in the CHOSeN deliverable *D3.3 Integration Report*, available for publicity at www.chosen.eu.

Finally the overall system, generically shown in Figure 21, has been used for building up application demonstrators of the developed CHOSeN technology in the automotive and aeronautic fields, by equipping the CHOSeN HW nodes with respective sensors. Further on, specific application SW on top of the middleware- and underlying protocol layers have been implemented upon the embedded application controller (EFM32) of the CHOSeN HW node.

Automotive Demonstrator

As highly challenging approach, a collision warning system, has been demonstrated.
The functionalities of the application aim to assess braking distance, safety distance and risk level; according to these parameters, the system gives an appropriate feedback to the user.
The CHOSeN middleware features, in particular the scalable communication hardware and adaptable protocols will constitute the enabling basis of this scenario.
Briefly, the WSN network evaluates almost in real time a chosen subset of dynamic parameters which are typical of a vehicle braking system and which can be integrated in an ADAS system. Thus measurements of vehicle dynamics and of environmental conditions must be acquired from a heterogeneous sensor system; the data are fused together and transmitted to the ADAS system responsible of situation refinement and of the possible consequent actuating actions (i.e. warning or mitigation).
The application works differently depending on the environmental conditions which can determine safety, alert or danger situation.
When the WSN network is not detecting any dangerous situation (Figure 26, left) the application does not need a high performance system. The whole sensor network works with low sampling frequency and low data rate communication, in order to save energy. In this state the most important network characteristic is to implement a very low-power communication that allows the data transmission (network management, data transmission …) with less possible system energy loss.
When one sensor node in the network detects a possible danger situation, for example one object in front of the vehicle within the sensed area or environmental dangerous situation (e.g. rain, ice, …), it wakes up the network and thus it maximizes the reactivity of the safety system (Figure 26, right).

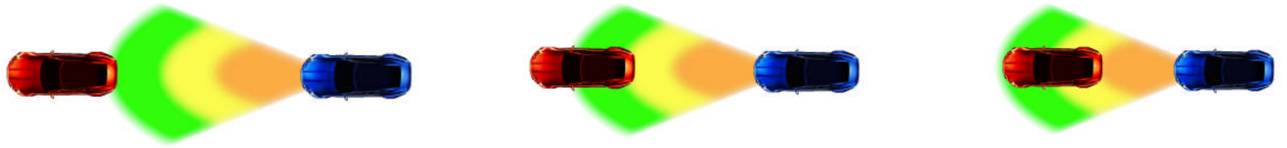

Figure 26: Collision warning system in “Safety Condition” (left), “Alert Condition” (middle), “Danger Condition” (right)

In order to have a quick and efficient system transition, it is essential to develop an appropriate wake up system. In the woken up mode, every network sensor acquires data with its proper sampling frequency and, after performing embedded data fusion, it transmits the processed data through the in-vehicle network. In this state the aim of the multi protocol communication layer is to provide a wide range of QoS, in order to support the required data rate required by each sensor type (Figure 26, middle). In this way, as the system has an heterogeneous group of sensors (radar, TMPS, Temp/Humidity …), it is possible to test the scalability of appropriate middleware features.
Differently from what it happens in the “safety condition”, where the efficiency is the most important network feature, in the alert condition the wireless network must enhance the responsiveness, reliability and robustness of the communication system.
When the system detects a danger situation due to a possible collision with another vehicle which is in the sensed area, i.e. when the braking distance is lower than the distance towards the frontal vehicle, the net must activate the actuator nodes and it must work with high responsiveness and robustness.
In this modality the communication layer must guarantee the management of multiple QoS, assigning different traffic profiles, in order to handle several priorities in case of high traffic load.
In addition to that it is also important to have a robust system of backup channels that could be accomplished by introducing the possibility of multiple communication paths. For power efficient implementation this application scenario therefore requires dynamic switching of MAC-layer as described as part of the supported Middleware QoS feature set.

A system with a high number of sensors has been simulated within the CHOSeN OPNET modeling framework. The physical automotive demonstrator has been realized with the following hardware components:

- 3 sensor node platforms
- 2 middleware node platforms
- 1 ALIX board
- 1 interfacing with the in-vehicle CAN bus
- 1 personal digital assistant (PDA)
- 1 sensor aimed at measuring the brake disk temperature (BDT)
- 1 sensor aimed at measuring the tyre pressure and temperature (TP, TT)

Those components have been mounted on the car as depicted in Figure 27, a Lancia Delta.

Figure 27: CHOSeN demonstrator car

The hardware components have been displaced inside the car according to the physical architecture depicted in Figure 28.

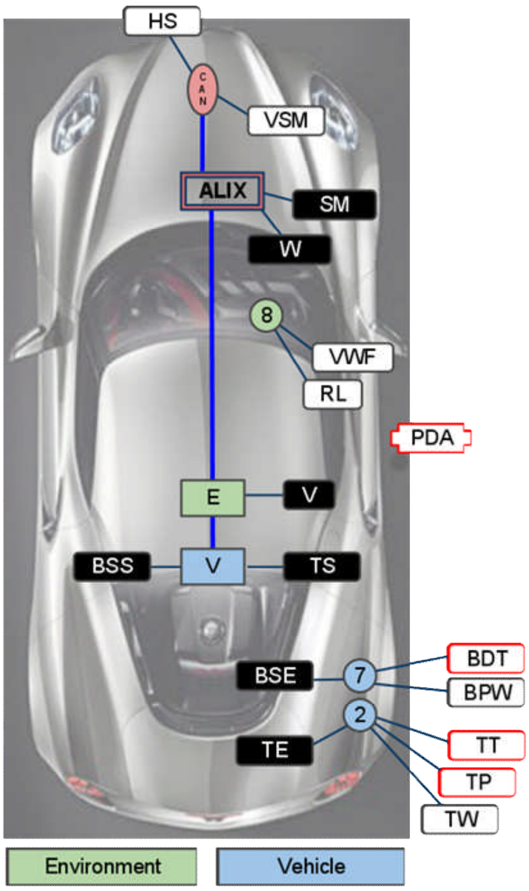

Figure 28: Physical architecture of the system prototype

The blue network is aimed at collecting measurements from the vehicle, mainly related to tyres and brake system. In particular, node 2 is equipped with an Infineon SP37 sensor, able to measure the temperature and the pressure of the tyre (TT and TP, respectively). The remaining “Tread Wear” (TW) value is simulated on the node. The three aforementioned L1 data are used to calculate the L2 data “Tyre Efficiency” (TE).
The second node of this network (node 7) is equipped with a TC Direct 401-130 K-type thermocouple, able to monitor the brake disc temperature (BDT). The “Brake Pad Wear” (BPW) value is simulated in order to be able to calculate the L2 data “Brake System Efficiency” (BSE).
The pictures of the nodes 2 and 7 are depicted in Figure 29 (a) and (b), respectively.


(a)

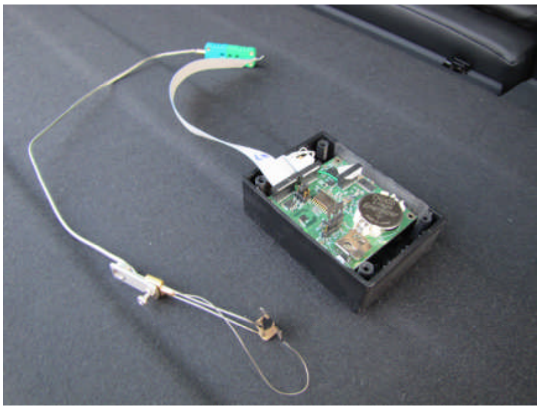
(b)

Figure 29: Node 2 (a) and node 7 (b) of the “Vehicle” wireless sensor network

The central node V collects the data necessary to calculate the “Brake System Status” (BSS) and “Tyres status” (TS) values. These last two quantities are related to the whole vehicle and should therefore be calculated using data coming from all the 4 wheels. However, in such a context only the available values are used to calculate them. The node V is located in the rear part of the car, as depicted in **Figure 30**.

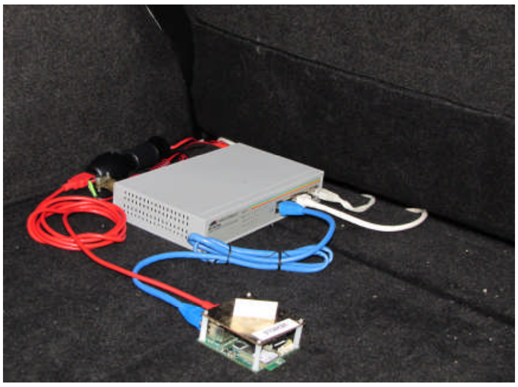

Figure 30: Node V of the “Vehicle” wireless sensor network

The green network collects data coming from the environment. The two quantities connected to the node 8 (“Visibility With Fog”, VWF and “Rain Level”, RL) have been emulated by using manual triggers connected to the analog interface of the platform.
These data are used in the central node E to calculate the “Visibility” (V). The nodes 8 and E are located in the cabin of the car, as depicted in **Figure 31**.

(a) (b)

Figure 31: Node 8 (a) and node E (b) of the "Environment" wireless sensor network

The two resulting subnetworks are connected through an Ethernet bus (straight blue line in Figure 28) to the ALIX board (the Ethernet switch used to create this local area network is visible in Figure 30). This embedded platform is also connected to the in-vehicle CAN bus in order to acquire the headlight status (HS) and the vehicle speed (VSM). This component collects the data coming from the two central nodes and from the CAN bus in order to evaluate the safety margin (SM) and to detect some possible warning or dangerous situations for the driver (W). For testing purposes, a data logger has been implemented on the ALIX board in order to acquire all the measurements taken from the wireless sensor networks.
A personal digital assistant (PDA) is finally integrated in the demonstrator in order to visualize all the data coming from the wireless sensor networks and also to warn the driver through visual alerts.

Three different scenarios have been considered, in order to prove the effectiveness of the overall architecture and to show the level of integration with the in-vehicle wired networks
The first application scenario takes into account a tyre that is slowly decreasing its inflating pressure.
The second application scenario considers a reduction of the visibility due to fog and rain.
In the third application scenario an issue of the brake system has been emulated.
It was verified that the application layer is able to acquire the data coming from the sensors and to correctly perform the appropriate data fusion algorithms. Moreover, the wireless networks promptly collect data in their central nodes to provide them to the ALIX board. This one performs further data fusion algorithms (also using data coming from the native in-vehicle CAN bus) in order to detect potentially dangerous situations for the driver. It is also able to share this kind of information with the driver through the Wi-Fi connected PDA. On the same device, it has been possible to follow the behaviour of the wireless sensor network by following the trend of each acquired measurement.

Aeronautic Demonstrator

For the anticipated support of system health monitoring, the use case scenarios shown and briefly described in
Figure 32 are of particular interest.

Monitoring of Door Surrounding (DSID-Door Surrounding Impact Detection)

- Monitor dents caused by gangways/ aerobridges
- Process data from groups of sensors to assess door area integrity
- On demand
- Moderate data rate (~100 kbit/s when measuring)
- Synchronized measurements of several sensors must be processed in order to assess health status of structure part
- Wake-up when gangway approaches

Crack detection

- Embedded in structure
- Very low data rate
- Transmission on demand and/or event-based
- Long lifetime (as long as airframe)
- Maintenance-free and autonomous
- Structure health assessment only possible with data from sensors at different locations
- Data fusion algorithms

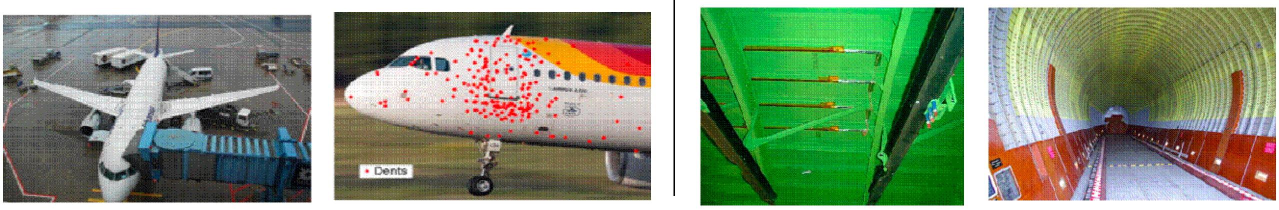

Figure 32: Aeronautic use-case scenarios

The main objective of continuous system and structure monitoring is the long-term maintenance-free operation of the wireless monitoring nodes to enable predictive maintenance support. That in term means that periodic battery exchange would be counterproductive because it would lead to a maintenance interval of the monitoring system shorter than the maintenance interval of the monitored systems and structure elements. Autonomous long-term operation means that the use of environmental energy for powering the wireless sensor nodes is an excellent solution. Of course the type of energy harvesting must be carefully selected according to the installation position of the monitoring nodes in the aircraft. Everything which is installed at the fuselage near the outside hull can be powered by taking advantage of the temperature differences between the cold hull and the warm inside. Even if the temperature difference is not always available, the electrical energy generated during the times where the outside and inside temperature is different can be stored. As prototype thermo-harvester devices with such power-management are available, they have been used for building up a self-sufficient WSN, by exploiting the ultra-low power operation enabled by the Wake-up receiver. The electrical energy generated during one flight (one take-off and one landing) with one such harvester device is in the range of 30 Ws (8.3 mWh). Figure 34 shows the energy profile of the thermo-harvester device recorded at two test flights. The flight test installation is shown in Figure 33.

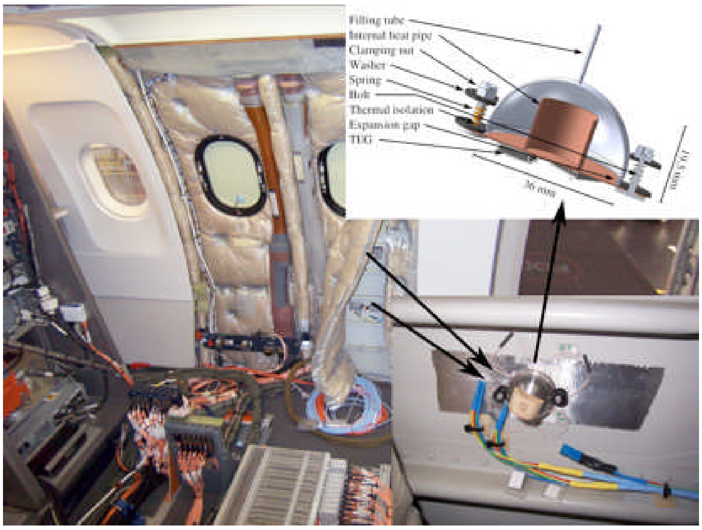

Figure 33: Flight test installation of harvester device

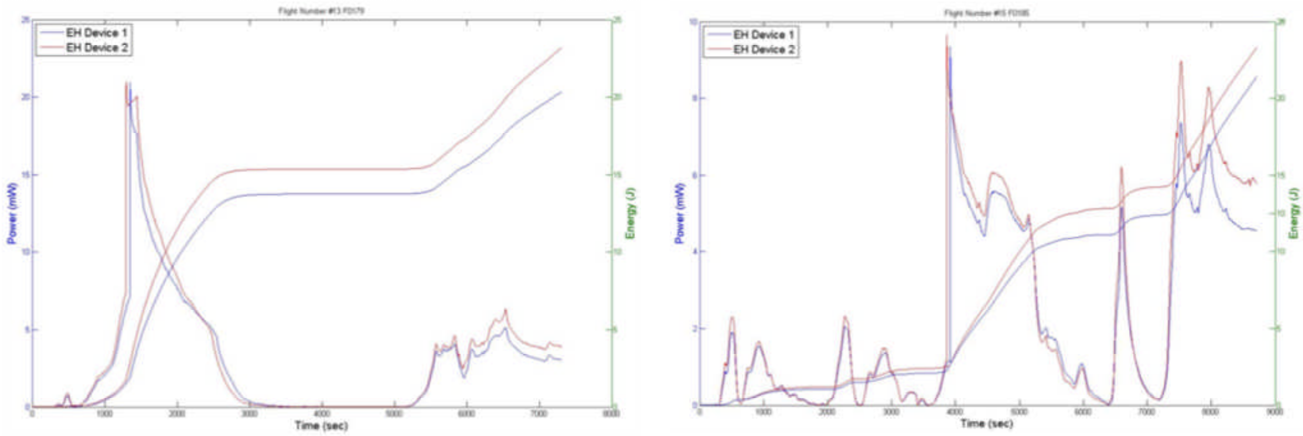

Figure 34: Energy profile of two different test flights (thermo-electric harvester from EADS IW attached to inside of fuselage)

In order to test the application performance regarding the energy limits and wake-up receiver performance a complete prototype was built including the harvester and power management modules. A prototype installation for the DSID scenario is shown in

Figure 35.

The aeronautic prototype has been built on an A320 door surrounding structure part. A wireless node has been fixed on the inside of that structure. It is connected to a power management platform with a thermo harvester. The harvester-powered node on the structure element is accompanied by battery-driven nodes, which can be distributed freely. One gateway node is used in order to discover the wireless nodes, configure their parameters like measurement interval, thresholds and transmission intervals as well as to collect the measurement data from the wireless nodes. The gateway node is connected to a Laptop via Ethernet, which is used for the application control and display software. With this prototype final assessments were done and measurements have shown that the power consumption of the CHOSeN node was within the limits of the energy generated by a harvester, stored in the power management; a reliable operation of the wake-up receiver is around 10 m, which is well within the limits of the application requirements. Also, the measured wake-up delay of less than 30 ms fulfills the aeronautic application requirements.

As a next step (not part of CHOSeN) CHOSeN-technology will be used for distributed temperature logging during test flights. For that reason Infineon has provided a small series of CHOSeN-chips to EADS.

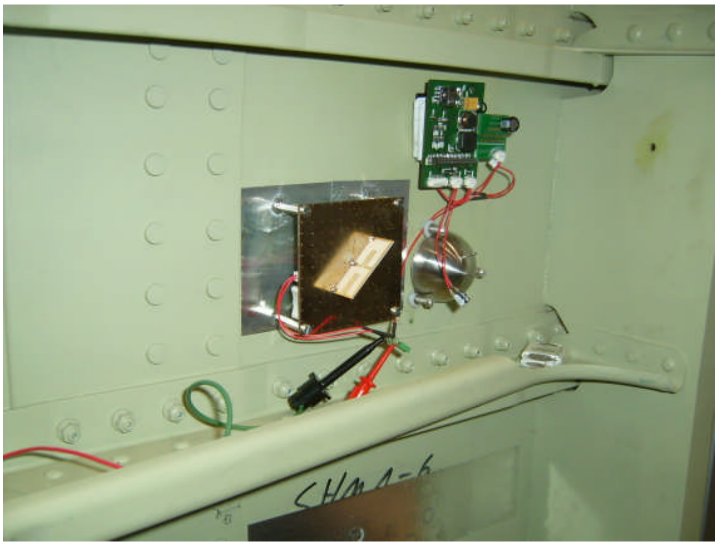

Figure 35: Test setup of aeronautic application demonstrator

3.8 Conclusion

Performance evaluation and comparison as well as application scenario feasibility simulations were performed and show that the CHOSeN node outperforms state-of-the-art sensor nodes in terms of power consumption in relation to achievable latency and throughput. The developed MAC protocols outperform standard MACs (802.15.4, X-MAC) in the relevant application scenarios. The application scenarios feasibility analysis showed that the CHOSeN hard- and software is well fitted in terms of the defined requirements.
An outstanding Wake-up receiver has been developed, which beats state-of-the-art receivers by a factor of ten in power consumption at comparable sensitivities. The sensitivity figure of -70dB meets the CHOSeN requirements due to the tense of sensor nodes to be installed in the targeted applications. For other industrial applications this sensitivity figure might be on the lower limit. Therefore there is room for further research to increase wake-up receiver sensitivity performance at comparable power values in order to extend the addressable application fields.

4 Impact, Dissemination and Exploitation

4.1 Strategic impact

With reference to the 7th FWP Objective ICT-2007.3.7, the main impact of the project for the automotive field is “New services and applications that are tailored to specific needs, seizing new market opportunities.”

The approached System Health Monitoring by Wireless Sensor Networks will open up new possibilities for applications in the industry. Complex systems fulfilling critical tasks needs to be monitored and maintained in order to guarantee their function. To do this, these systems must be disassembled, audited, reassembled and tested. Often, the downtimes of such complex systems can hardly be afforded and the maintenance costs are significant. Obviously cooperating wireless sensor nodes would be of great benefit for the continuous measurement of critical physical data. Together with flexible communication protocols enabling the easy registration, configuration and supervising of the installed sensor nodes, the system health of different complex systems could be monitored quite efficiently. This would allow:

- New applications and services not achievable with current technologies
- Significant reduction of downtimes and maintenance costs

Several research and engineering steps are necessary to reach these goals. A concept of a configurable, power saving and robust wireless node interfacing to various sensor types has to be developed. The hardware, especially a power saving transceiver, must be designed and implemented, flexible and reliable communication protocols has to be designed supporting the auto-configuration, power-saving and data distribution capabilities of the wireless nodes. To enable the easy installation of new measurement points, the monitoring of a wide range of system sizes and the integration of existing - possibly wired - sensors, a new middleware platform must be developed supporting the heterogeneous nodes, automatic resource discovery and management and the presentation of the collected data and system status to the higher protocol layers.

The impact of WSN in industrial application is schematically represented in Figure 36.

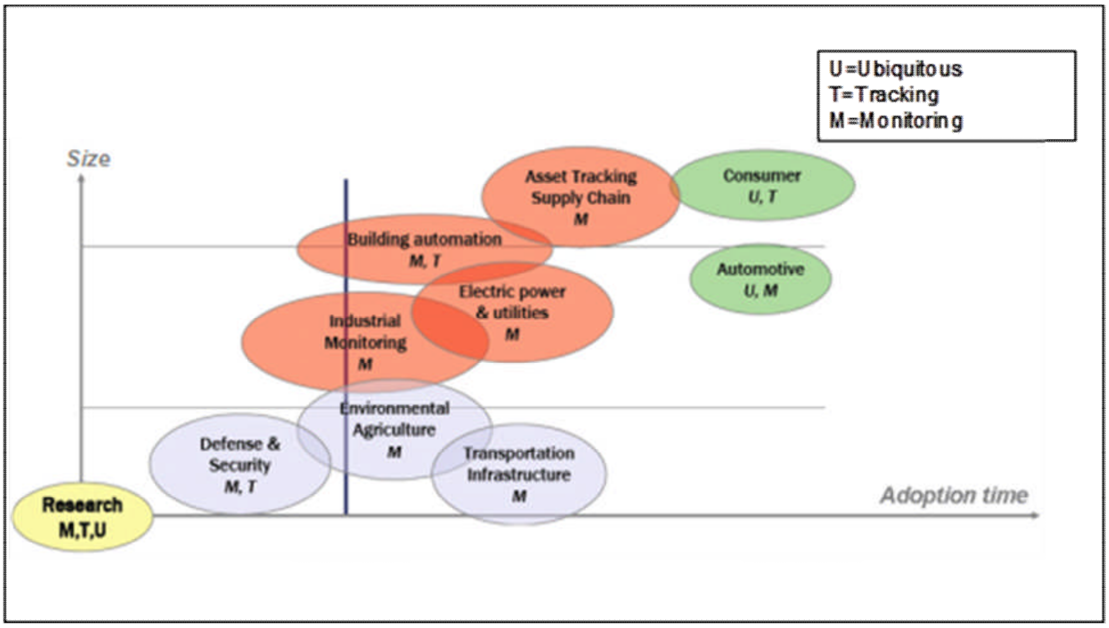

Figure 36: WSN impact on industrial applications

The market penetration of WSN in automotive field is expected to take place from 2014. In this context *CHOSeN* addresses the improvement of WSN technology and contributes to the following improvements linked to the connectivity optimisation and extension:

- The integration of information coming from previously inaccessible nodes allows to define new applications or improve/extend existing ones
- Presently the aftermarket devices are limited in their functionality by the lack of connection with the vehicle network. Interaction between PAN and in-vehicle WSN enables to integrate in a single network the data coming from different source peripherals
- Externally driven applications monitoring the vehicle sensor status can be easily connected

Beyond these application advantages, WSN have further impacts due to the reduced presence of cables in the vehicle, which are here mentioned as they strongly contribute to the general economic impact.

- Reduction of the vehicle weight with subsequent enhancement of vehicle performances

- Possibility of using standardised connectors instead of the ad hoc connectors which are used now-a-day when interfacing a new node with the vehicle CAN.
- Reduction of maintenance and installation costs.

4.2 Contribution to expected impact

Cooperating objects and wireless sensor networks have two aspects, the enabling network technology and the use case needing cooperating objects. *CHOSeN* meets exactly these prerequisites.

Wireless network: ▪ **generic enabling technology** ▪ **immense utilization potential in innumerable civil and military applications**	**System health monitoring:** ▪ **use case, vertical integration**
▪ Wireless ▪ energetically closed ▪ bit/energy maximized ▪ sleeping function ▪ P2P ▪ Data read out at every node ▪ topology aware and adaptive ▪ scaleable ▪ fault resistant and adaptive ▪ reconfigurable to changes in tasks ▪ spatial spread aware ▪ flexible application plug in	▪ sensors pluggable on nodes ▪ sensor-data fusion configurable on special capable nodes for further processing ▪ allowing a heterogeneous integration of suppliers sensors, wear models, diagnosis systems and in the future also reactive systems ▪ resulting in a heterogonous distributed system collaborating for optimal health monitoring, system saving, maintenance optimization and use optimization

Table 4: The two foci of *CHOSeN*

EADS and CRF are integrators interacting with innumerable suppliers for constructing complex integral systems. System health monitoring is just one but a good example bringing to interplay different sensors from different suppliers, ensuring their communication and data flow, bringing the data to knowledge used by wear and diagnostic models also delivered from different suppliers for optimal system health management as a basis for both optimizing failure modes when the system is in use and for maintenance optimization so optimizing system use. Spontaneous cooperation of the heterogeneous integrated communication / sensor / data processing / monitoring nodes in a topological and spatial optimized manner is the prerequisite of the integrator – supplier technological architecture. The wireless technology is needed for certifiability aspects.
Therewith certifiability leads also to energetically closeness based on intelligent sleeping functions and the optimisation of bit/energy in principle. The system must be self organizing with respect to energy needs for sensors, sleeping functionality residuals, communication as a function of the topology and spatial spread of the distributed sensor – monitoring system. So can topological communication bottlenecks run out of energy cutting off big parts of the net from communication in the sense that the weakest link of the chain stops the function of the system. Besides that this must be avoided the opposite must be enforced, making the network fault resistant concerning topological and spatial uncertainties, nodes availability, bandwidth problems e.g. by topological redundancies, topological self-organizing or by adaptively enhancing communication emitter energy based on dynamic resource management, respectively.
Redundancies imply protocols allowing a change in the nodes roll collecting sensor data, enabling communication issues, for data read out and all that resources, failure or task adaptive.
Today 3.1 million people are employed in the air transport industry in Europe. Traffic growth is expected to double in 15 years and lead to air transport contributing up to 13% of Europe's GDP.

To meet that challenges ACARE has located technology areas, taxonomy areas and has evaluated research efforts in its Strategic Research Agenda 2 (SRA-2), see Figure 37. Amongst others, aero structures, propulsion, avionics show highest future research efforts in combination with cost efficiency and ultra green. These are the points *CHOSeN* is focusing.
CHOSeN addresses cost efficiency directly via being a basis for use and maintenance optimization. Even more efficient will be secondary effects via enhancing certifiability of future technologies by system health monitoring paving the way to new technologies like lightweight construction using new technologies like CFK technologies and related efficient production technologies. It allows new technologies like the all electric aircraft for saving further weight and getting rid of the poisonous hydraulic fluids (helping to get the ultra green aircraft). It ensures the functionality of future redundant avionics systems allowing integral aircraft redundancy paradigms based on systems health monitoring by adaptive control allowing safety flight envelopes adaptive to all over the aircraft malfunctions.

Today a civil aircraft has unscheduled events above 60% resulting in aircraft grounding and so in a loss of usage. In the moment we have a push to new technologies meeting the cost efficiency and ultra green demands resulting in unscheduled events much above that figure. We expect the *CHOSeN* technology to push down this figure a magnitude getting close to 100% aircraft availability by adaptive usage extension keeping the system alive in certified modes even in the presence of failures.

Figure 37: Indicative research intensity by technology area [1]

Scheduled events (regular maintenance events) costs can be reduced almost by a factor of two by maintenance optimization (= calculating optimal maintenance extant and dates) based on items live prediction extracted from the wear a diagnosis models. We are talking here about maintenance on demand. It's a known fact that maintenance on demand can used for both, minimizing costs "and" enhancing safety.

Future redundant avionics systems will allow integral aircraft redundancy paradigms and in combination with adaptive control will allow safety flight envelopes adaptive to all over the aircraft malfunctions detected by system health monitoring reducing accidents also covering human mistakes.

So, in spite a the multiplication of future aircraft complexities, *CHOSeN* will be a threefold enabler

- pushing new technologies (light weight material, all electric),
- while enhancing safety, and

[1] ACARE Advisory Council for Aeronautics Research in Europe, October 2004, Strategic Research Agenda 2

- optimising maintenance.

The *CHOSeN* Project will allow the operator to have a better confidence in its vehicle (car or aircraft) and in the reliability of the complex systems:

- Operational availability
  The period where a vehicle (car or aircraft) is not usable will be reduced. Thus, a switch to other means of transportation is not necessary and the overload or cascading effects on mass transportation or transportation media can be reduced. Furthermore, the unexpectedly breaking of part of a vehicle will be minimized.

- Maintenance
  For maintenance or crew teams, the understanding of the vehicle's status will be re-enforced. It will allow them to take a better decision when in operation, detect imminent problems earlier to assign urgent and un-scheduled maintenance, and to decrease scheduled maintenance cycles as a better information base of the vehicles status exists. The availability of the vehicle will be optimized.

- Safety
  By improving the level of safety, *CHOSeN* ensures reduction of preventable accident. This will also lead to benefits in terms of reduced environment damage, reduction in cost and increase in the perceived user comfort.

- Employment
  Having in hand the *CHOSeN* technology for the European aeronautical and automotive industry will allow it to maintain its high level of performance of end products in a strong competitive market.
  It will also enable the European industry to play a major role in the sensing and monitoring industry by bringing new concepts and therefore being in a strategic position to increasing its market share.

- Costs
  As already discussed, the life cycle costs and the direct operational costs will be decreased

Generally, *CHOSeN* with its approach widens the application space covered by a single solution. It brings a significant contribution to introduction of new technologies for aeronautic and automotive industry. Generic *CHOSeN* results may in future play an impact to other industries that use varying systems like transportation, robotics, and industrial activities. Those technologies are providing better operational features improving security by reducing implementation and operation cost.

4.3 European added value

Due to the nature of the objectives of the *CHOSeN* project and the high level of skill needed, it is essential that major technology providers and manufacturing industry partners are working together to jointly provide an significant functional, technology and economic impact on European aerospace as well as automotive level.

Moreover due to the nature of the participants and their R&D and industrial involvement on other fields, working at the European level is a chance from capturing the best state of the art of the critical technology to jointly adapt it for avionics and automotive needs.

In return, the knowledge has been directly spread not only in the aeronautic and automotive industries but will also impact other industrial sectors.

CHOSeN will allow the European industry to consolidate its position by setting the adequate partnership for future product development and re-enforce its position in front of external competition. It may give a chance to take a strategic advance and a key position in future associations.

Due to the very strong *CHOSeN* Consortium, the European know how in the key technologies will join to provide the essential benefits to the European aviation and automotive industry.

4.4 Dissemination & Exploitation

Extensive dissemination activities have been performed by the CHOSeN consortium partners. Dissemination activies include

- Hosting of a project Web page
- Publications at renowned European conferences
- Partner internal workshops
- Business partner workshops (hosted and informal)
- Creation of advertising material
- Adoption of gained CHOSeN know how into University teaching

At the end of the project CHOSeN consortium partners held the “CHOSeN Days” event in the show room of EADS IW in Ottobrunn, Germany. Each partner presented its work and advances in the project by means of presentations, poster sessions and live demonstrations of the CHOSeN technology in the automotive and aeronautic scenarios. This event represented the culmination of the project, and served as a major dissemination event with ramifications for exploitation both inside and outside individual companies and projects. In Figure 38 some impressions are given.

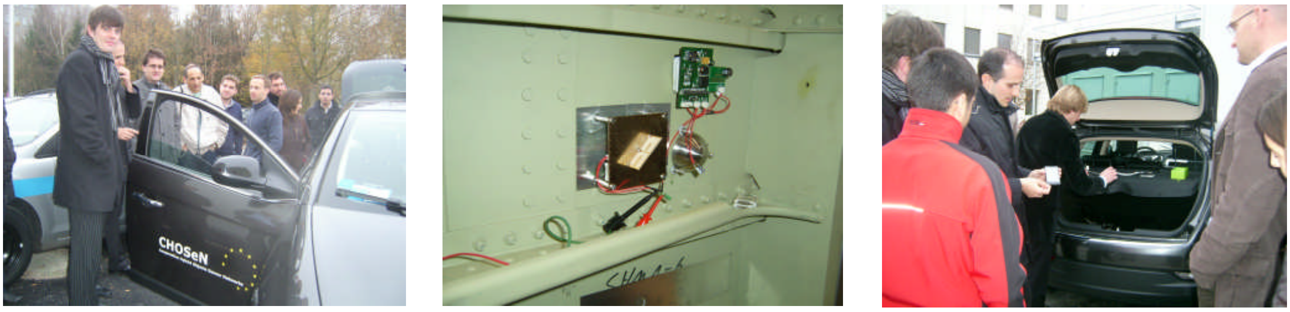

Figure 38: Pictures from the “CHOSeN Day”

The presence of major European industrial players (EADS, CRF, Infineon) in the consortium will enable rapid commercialization of the project outputs, enhancing European competitiveness in the global transportation market and ultimately leading to new high technology jobs for European workers. It is expected that the involved SMEs (ACCORDE, ARDACO) will increase their revenue thanks to products based on the project results. The technology developed throughout CHOSeN will be able to drive down operational costs and CO2-emissions due to weight-reduction and will contribute to a greener world. Further on it will raise the level of passenger safety. The know-how and new insights gained by the academic and research partners (TUV, TUG, KIT, LETI) will lead to highly skilled next generation students and PhD-candidates.

5 General Information

CHOSeN Web-Page:
www.chosen.eu

Public available project reports at www.chosen.eu:

- D1.1 Requirements analysis document for automotive applications
- D1.2 Requirements analysis document for aeronautic applications
- D1.3 Description of the automotive demonstrator
- D1.4 Description of the aeronautic demonstrator
- D2.2 System model definition and simulation results
- D3.3 Integration report
- D4.4.1 Field trials and assessment report for automotive application
- D4.4.2 Field trials and assessment report for aeronautic application
- D5.3 Dissemination & Exploitation report

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