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Capability Project

LPS and sensor node system architecture

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ABBREVIATIONS AND ACRONYMS

ABBREVIATION	DESCRIPTION
6lowPAN	IPv6 over Low power Wireless Personal Area Networks
AC	Alternating Current
ADC	Analogue to Digital Converter
AES	Advanced Encryption Standard
AODV	Ad hoc On-Demand Distance Vector
ASIC	Application-specific Integrated Circuit
B.A.T.M.A.N	Better Approach To Mobile Ad-hoc Networking
CAN	Controller area network
CPU	Central Processing Unit
DBMS	Data Base Management System
DC	Direct Current
DFS	Dynamic Frequency Selection
DSSS	Direct-sequence spread spectrum
ECC	Electronic Communications Committee
EEPROM	Electrically Erasable Programmable Read-Only Memory
EGP	Exterior Gateway Protocol
EIGRP	Enhanced Interior Gateway Routing Protocol
FCC	Federal Communications Commission
FFD	Full-function device
FMCW	Frequency-Modulated Continuous Wave
FPGA	Field Programmable Gate Array
FPGA	Field Programmable Gate Array
GDOP	Geometric dilution of precision computation
GPRS	General Packet Radio Service
GPS	Global Positioning System
HTTP	Hypertext transfer Protocol
HW	Hardware
HWMP	Hybrid Wireless Mesh Protocol
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISM	Industrial-scientific-medical
LAN	Local Area Network

ABBREVIATION	DESCRIPTION
LSN	Local Sensor Network
LOS	Line-of-Sight
LPS	Local Positioning System
LPS	Local Positioning System
MAC	Medium Access Control
MEMS	Microelectromechanical Systems
MODBUS	A serial communications protocol
NTP	Network Time Protocol
OFDM	Orthogonal frequency-division multiplexing
OLSR	Optimized Link State Routing Protocol
OLSR	Optimized Link State Routing
OSPF	Open Shortest Path First
PAN	Personal Area Network
PCCDN	Post Crisis Needs Assessment Tool in regards to Construction Damage and related Needs
PLME	Physical Layer Management entity
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RECONASS	Reconstruction and REcovery Planning: Rapid and Continuously Updated COnstruction Damage, and Related Needs ASSessment
RF	Radio Frequency
RF	Radio Frequency
RFD	Reduced-function device
RS485	Serial interface standard in which data is sent in a differential pair
RTK	Real-time Kinematic
RTLS	Real Time Location System
SAP	Service Access Point
SBAS	Satellite-based augmentation service
SD	Secure Digital
SEED	Standard for the Exchange of Earthquake Data
SPS	Samples per second
SRAM	Static random-access memory
SRD	Short range device
SSID	Service Set Identifier
SSL	Secure Socket layer
SW	Software

ABBREVIATION	DESCRIPTION
TCP	Transmission Control Protocol
TLS	Transport Layer Security
UDP	User Datagram Protocol
USB	Universal Serial Bus
VLAN	Virtual Local Area Network
WAN	Wide Area Network
WDS	Wireless distribution system
WEP	Wired Equivalent Privacy
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access
WSN	Wireless Sensor Network
xDSL	Symmetric digital subscriber line
ZC	ZigBee Coordinator
ZED	ZigBee End Device
ZR	ZigBee Router

GLOSSARY OF TERMS

Accelerometer	A sensor that measures the specific force (i.e. acceleration).
Accuracy	Deviation of a measured value to a reference value.
Anchor	Any sensor node with known reference position that communicates with other nodes to give them reference location data.
Coordinator or base station	Connected to a certain number of LPS sensor nodes, coordinates positioning signals, calculation of position of each node relative to anchor, interface to the rest of the monitoring system.
Data hub	Data hubs will be used to locally collect all data from the different sensors (acceleration, strain, temperature, position), then transfer this data to the gateway.
Gateway	The communication's module central unit where sensor collected data is aggregated, formatted, classified, validated and finally transmitted to the PCCDN tool for further processing and subsequently overall structural and non-structural assessment. Furthermore, the underlying sensor network is monitored and managed through the RECONASS gateway in a way that ensures the network is operating efficiently mainly in terms of availability, reliability and power consumption.
LAN	Local Area Network – (see Figure 25) LAN access specifies the various interfaces between the gateway and the data-hubs and the communication means deployed between the data-hubs and the sensors.
LSN	Local Sensor Network – (see Figure 25) LSN access specifies the interfaces and the network deployed between the wireless/wired sensor nodes and the data hubs.
Precision	The repeatability of a distance or position measurement in an unchanged scenario.
Resolution	The ability of the LPS to separate targets (i.e. tags) in close proximity.
Sensor node or tag	Small locatable device to be embedded at crucial points such as beams and columns in the structure. Certain external nodes will be provided with access to GPS.
Strain gauge	A strain gauge is a device used to measure strain on an object.

EXECUTIVE SUMMARY

This document D2.1 is the first deliverable in work package 2 in the RECONASS project and it is about the LPS and sensor node architecture for the RECONASS system. Following on from the 'Full specifications' deliverable (D1.4), with an output of specifications and operational and performance parameters that RECONASS should have, we will use the results as a benchmark to select and design the needed sensor nodes and interfaces.
This deliverable document includes the architecture of the LPS and the different sensors used in the RECONASS system and their interfaces to the monitoring system, including:

- local positioning tags,
- network of sensors (acceleration, temperature and strain),
- data hubs (for collecting the sensors and tag data) and communication gateway module (to gather all the data in the appropriate format).

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The different technology domain/system components were represented in each chapter of the deliverable (each representing a system component).
In order to derive the system architecture, teleconference meetings and a face-to-face plenary were held to discuss the possible system specific components and architecture. Each project partner contributed following a proposed structure as follows:

- Review the specification deliverable document (D1.4) to identify which components are needed to define the architecture and sensor nodes of RECONASS.
- Then for each sensor component, define performance parameters and physical specifications.
- Then select or design the sensors which fit the performance criteria.
- Finally, define the necessary interface of each sensor in the commutation module to convoy sensory data to the PPCDN tool.

As this is a research project, this document actually represents the initial system architecture and as the research and development activities unfold then the final system and components of the system will be revealed.

INTRODUCTION

RECONASS Project Overview

RECONASS aims to provide a monitoring system for constructed facilities that will provide a near real time, reliable, and continuously updated assessment of the structural condition of the monitored facilities after a natural or manmade disaster. The above assessment will be seamlessly integrated with automated, near real-time and continuously updated assessment of physical damage, loss of functionality, direct economic loss and needs of the monitored facilities and will provide the required input for the prioritization of their repair.
Still another aim of RECONASS is to provide seamless interoperability among heterogeneous networks to secure that the required information from the monitored facility can reach, in near real-time, the base station even after difficult conditions, such as post-crisis situations.
In order to achieve its objectives, RECONASS will develop small, inexpensive, wireless, local positioning tags that will be embedded in the structural elements of the monitored buildings to report their position to the base station. Following a disaster, comparison of the original position of the tags – in the undamaged state – with the final position of the tags – in the damaged state – will be used in order to hypothesize the structural system that has emerged from the disaster. This latter system, then, will be used to assess the structural response, damage and loss.
To ensure that the positioning, acceleration, strain and temperature information from the monitored buildings can reach the base station, a gateway-PCCDN tool for communication will be developed that will provide redundancy at situations of access network unavailability by utilizing multiple and different access interfaces, e.g., GSM, UMTS. Remote sensing-based damage maps will be provided, using both air- and space-borne imagery. Near real-time construction damage data from the monitored buildings will be used in order to effectively calibrate and evaluate these maps.
Based on the above, a PCCDN Tool will be developed in RECONASS that will provide the recovery stakeholders with near real-time, detailed and reliable data and information on the construction damage, loss and needs of monitored buildings, continuously updated, and space borne and airborne damage maps (calibrated and validated for the buildings monitored) in a much reduced time, fused and integrated with relevant external data and information. This Tool will provide international interoperability, allow for customization and expansion and permit collaborative work between the civil agencies/authorities and the relief units.

Framework

The purpose of this deliverable is to define the architecture and the interfaces of the system components based on the requirements –user and technical- defined in D1.4. A preliminary set of specifications has been also established per component base within D1.4, however in the scope of WP2 and its first deliverable – D2.1 – the work focuses on refining them and further advancing on specifying the LPS and sensor node system architecture on a close-to-hardware level.

Description of the contents

Chapter 1 describes the local positioning system and the proposed tags-coordinator LPS topology and structure. Moreover, it gives some details about the proposed GPS aiding.
Chapter 2 describes the physical details of the strain, acceleration and temperature sensors and their performance parameters.
Chapter 3 describes the communication module and its components of gateway, data hubs and the sensors interface. It describes the overall means of communication and interfaces deployed in order to effectively receive data from the sensors' ecosystem and subsequently convey them to the PPCDN tool where the structural/non-structural assessment will take place.

1. THE LOCAL POSITIONING SYSTEM ARCHITECTURE (LPS)

1.1. The proposed tags-coordinator LPS topology and structure

1.1.1. Terms

Regarding LPS performance, there are three basic terms, which are sometimes mixed and are therefore defined below:

- **Resolution** is the ability of a LPS to separate targets (i.e. tags) in close proximity. Resolution usually increases with the bandwidth of a system. A system with bad resolution will show two closely spaced targets as one.
- **Precision** is the repeatability of a distance or position measurement in an unchanged scenario. It does not contain information on constant systematic errors or biases. A good precision means that the variance of a measurement series is small.
- **Accuracy** is the deviation of a measured value to a reference value. Accuracy in a LPS can only be defined when a ground truth reference is available.

1.1.2. LPS system architecture and distributed nodes configuration

Possible solution and system architecture considering a three-story building (12.5*5*7.5) planning:
Consider the following structure of a three-storey building. The nodes can be mounted in a case inside the wall or outside and attached to the beams and columns of the building. The measuring point of the tag position is the antenna. Its mounting has to allow maintenance access to the system. Furthermore the antenna of the RF front end needs to see free space. A possible architecture for the two-way signalling scheme is depicted in Figure 1.

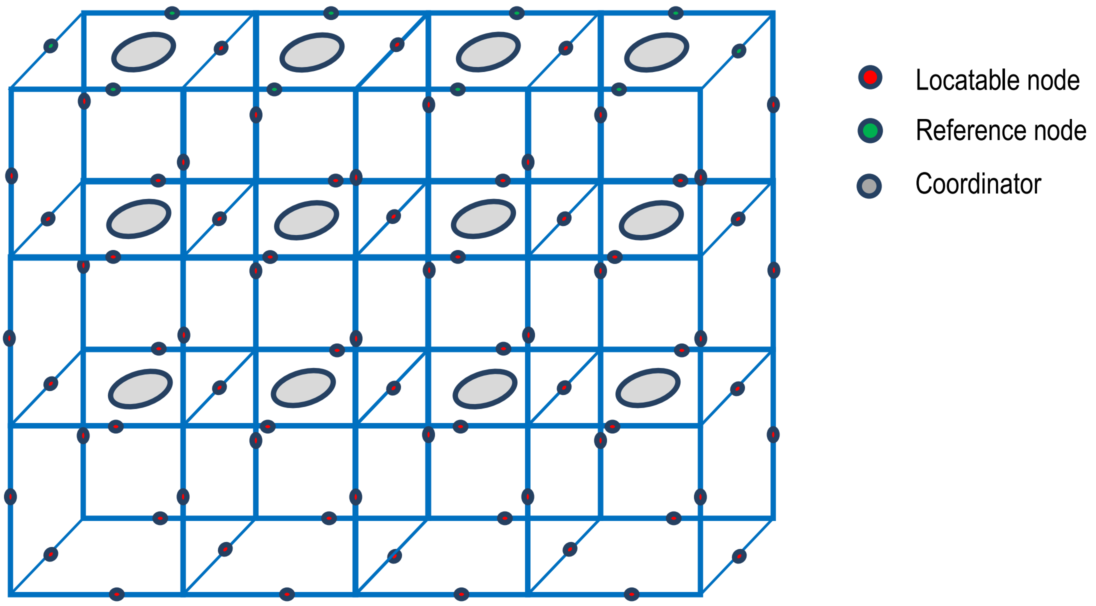


Figure 1-Possible LPS node distribution in SHM application (locatable nodes in red, reference nodes in green, coordinator in grey)

Sensor node or tag: small locatable device to be embedded at crucial points such as beams and columns in the structure. Certain external nodes will be provided with access to GPS. Once those sensor nodes were assigned accurate locations by the rest of the system they become anchors.

Anchor: is any sensor node with known reference position (by GPS or by direct measurement of distances to other nodes) that communicates with other nodes to give them reference location data.
Coordinator or base station: connected to a certain number of LPS sensor nodes, coordinates positioning signals, calculation of position of each node relative to anchor, interface to the rest of the monitoring system. To determine sensor node locations, each node makes contact with at least three already positioned tags. All the tags can communicate with each other to be able to find their positions in a 3D coordinate system. It is beneficial to use more than three GPS-enabled nodes to have a better geometric dilution of precision computation (GDOP) factor and to conduct research on how to benefit from the measured distance between nodes in correcting the GPS measurements. Installed accurate GPS-enabled nodes on the roof, 10 accurate nodes as shown in **Error! eference source not found.** to reduce costs, can supply accurate position to the whole configuration as they can serve as accurate beacons to the remaining tags. The coordinator can be installed on a per-room basis, where it connects to a certain number of nodes. The coordinator nodes are mounted to the ceiling inside the room so they can communicate with all nodes installed within the room.

Accurate reference position challenge in RECONASS
A major challenge to be considered is that the localization system determines positions of tags using reference stations. Since both, tags and reference stations, are mounted to the building structure, they are both susceptible to movements during building damage. As a result, the reference is shifted and the position of the tags cannot be determined anymore. This challenge is planned to be handled by using one accurate real-time kinematics (RTK) GPS which serves as a guide to other low-cost GPS modules. This cost-effective solution will give positions to all tags and coordinators in a global coordinate system with WGS84 format. Figure 2 shows the planned LPS network architecture and its placement in a building.

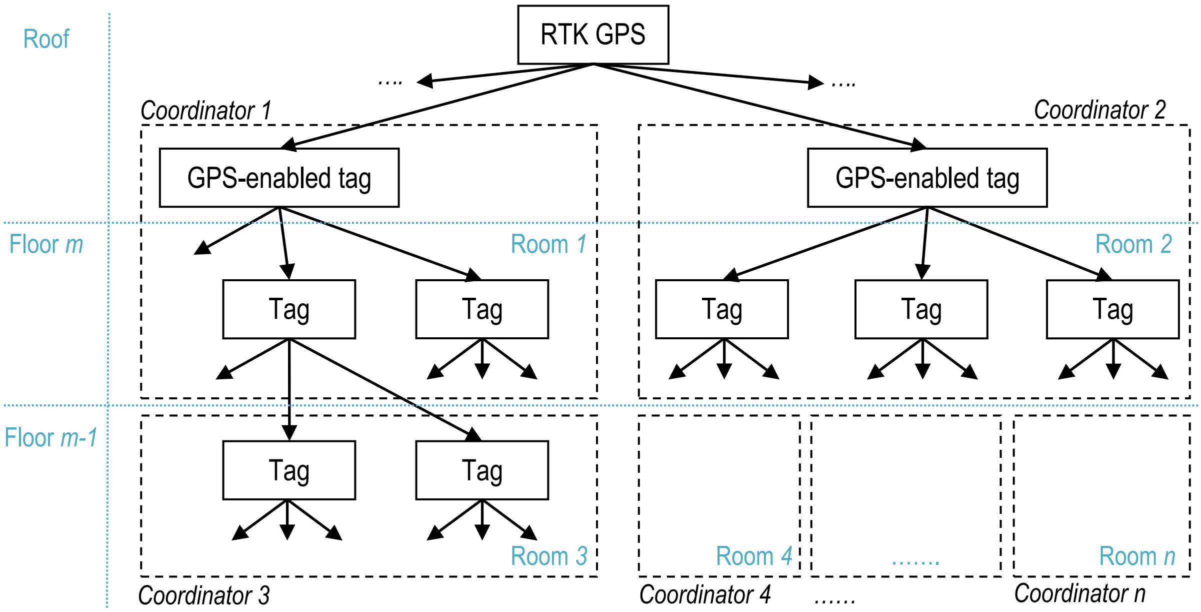


Figure 2-LPS network structure and placement in building with roof, m floors and n rooms

The RTK GPS reference system will be placed on the roof or outside of the building together with all GPS-enabled tags to get a good reference signal. For each room, a coordinator is employed, which connects to a certain number of tags (GPS-enabled or regular). The number of tags per coordinator is theoretically unlimited, but a practical limit is set by the round-trip delay of the measurement, which determines the update rate of the system. Around 10 tags per coordinator can be feasible. The tags on a certain floor connect again to neighbouring tags in lower floors, creating a tree-like structure. The algorithm for positioning is envisioned to work as follows:

1. The location of the roof reference is determined with RTK GPS.
2. All GPS-enabled tags determine their positions, using the data from the RTK GPS for error correction.
3. The newly positioned tags operate as anchors, now that their position is determined.
4. Neighbouring tags (e.g. in lower floors or adjacent rooms) are positioned using those anchors.

5. The algorithm repeats the positioning procedure from step 3 until all tags in the building have determined their positions.

1.1.3. Integrated circuit approach

The RECONASS tag and coordinator hardware uses an application specific integrated circuit (ASIC) for transmitting, receiving and processing radio frequency (RF) localization signals. The localization scheme will be based on secondary frequency-modulated continuous wave (FMCW) radar as shown in Figure 3.

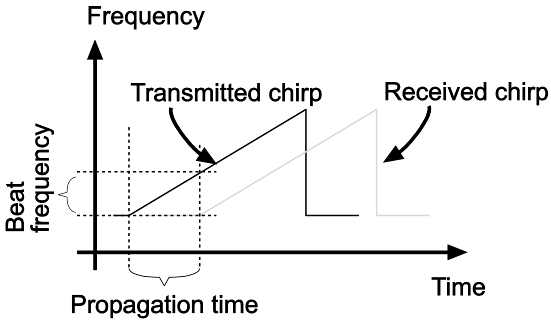


Figure 3-FMCW radar chirp signalling scheme

The FMCW radar uses frequency chirps with a certain bandwidth. Receivers for frequency modulated signals are well researched in literature and therefore are easy to implement. The depicted graph plots frequency versus time and shows two frequency chirps: the first one is the transmitted one by a station and the second one is the received delayed signal either by another station (secondary radar) or by a reflector (primary radar). During the time both chirps overlap, there is a difference frequency (beat frequency), which is directly proportional to the delay between the transmitted and received signals and therefore the distance between the targets. Technically, the difference frequency is detected by multiplying both signals with a frequency mixer and then calculating the spectral representation of the resulting signal with a Fourier transform.
Since the system is supposed to work in the RF domain, suitable frequency bands for operation have to be specified. To determine which frequency bands are suitable for a LPS, several constraints need to be considered. A large chirp bandwidth is crucial for good resolution. Also, frequency bands with higher centre frequency usually offer larger bandwidths. Opposed to that, path loss increases for higher frequencies, thereby limiting the range of the system and decreasing the ability of the signal to penetrate obstacles in non-line-of-sight environments. Hence, staying below 10 GHz poses a suitable compromise between range and bandwidths since two large worldwide license-free industrial-scientific-medical (ISM) bands at 2.4-2.4835 GHz with 83.5 MHz and 5.725-5.875 GHz with 150 MHz bandwidth are available according to the *Electronic Communications Committee (ECC) Recommendation 70-0* [9]. Federal *Communications Commission (FCC) Part 18* [10] even allows 100 MHz bandwidth in the 2.4 GHz band, which will be used for the design. Since the system will be designed fully configurable, bandwidths can be switched according to the local regulations.
Because the targeted range is relatively low (subsystem consisting of coordinator and tags on a per-room basis) and so are the transmit powers, the system can be classified as short range device (SRD). SRDs describe radio frequency (RF) devices having low capability of interfering with other radio equipment. The *ECC recommendation* defines the powers for SRDs in the specified ISM bands as 20 dBm equivalent isotropically radiated power (EIRP) at 2.4 GHz and 14 dBm EIRP at 5.8 GHz.

The block diagram shown in **Error! Reference source not found.** presents a possible implementation of the LPS ardware using the FMCW principle with capability to operate in both specified bands. It consists of an FMCW ASIC and a digital module (e.g. *Spartan6 Field Programmable Gate Array (FPGA)* Module [11]). Furthermore, there is a frequency shift keying (FSK) module. Other than that there are some other external components, namely the phase-locked loop (PLL), band filters, switches, two power amplifiers (PAs) and an analogue-to-digital converter (ADC). The function of the modules is described below:

- **FMCW ASIC**: It integrates the most important parts of RF signal processing, which is a low noise amplifier (LNA) for amplification of the weak received signal, mixer for down-conversion to base band and a base band variable gain amplifier (VGA) to further amplify the signal before driving the ADC.

Furthermore, the local oscillator (LO) signal is generated by a voltage-controlled oscillator (VCO) on-chip, including buffers and frequency dividers to work in both specified bands. Together with the external PLL, the VCO forms a stable and programmable LO frequency source. Lastly, the ASIC contains PA drivers to drive both external PAs for the 2.4 GHz and 5.8 GHz bands. Using external RF switches, the signal path can be selected for both bands and for transmit or receive.

- **Spartan6 Module:** This module handles digital base band signal processing, i.e. Fourier transform, distance and position calculation. Furthermore it controls the ASIC and other external components. In case of the coordinator, it can contain wireless interfaces (ZigBee, Wi-Fi) or Ethernet.
- **FSK Module:** This module is used for protocol handling and coarse synchronization between the coordinator and tags. It is a dedicated module, because protocol handling in a LPS is a time critical process.

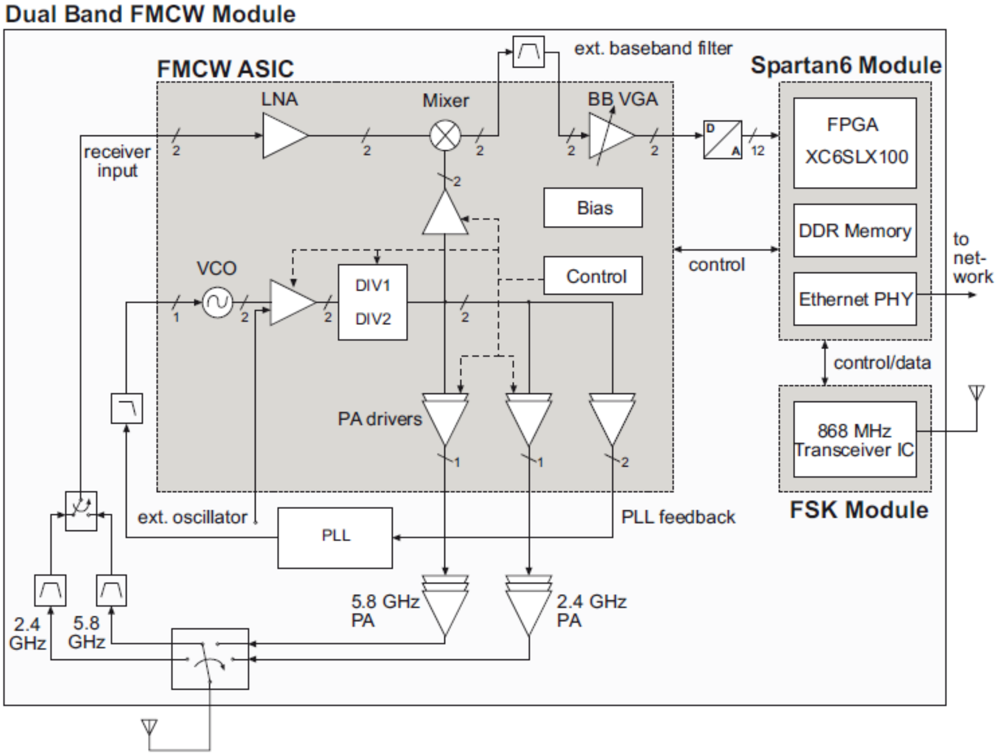


Figure 4-Possible LPS module architecture with FMCW principle [12]

A prototype ASIC used in the *European Integration Project E-SPONDER* is depicted in Figure 5. It was designed in a 180 nm BiCMOS technology, measures only 1.56 mm² and contains most of the Analogue signal processing with the exception of a phase-locked loop (PLL) for chirp frequency stabilization and power amplifiers (PAs). The RECONASS system aims for an increased level of component integration by adding the currently external PLL to the chip. A high level of integration allows small form factors, lower power consumption and less cost in mass fabrication. Furthermore, it might be feasible to also remove the dedicated FSK module and integrate it with the transceiver in the chip. This allows saving further board space and power.

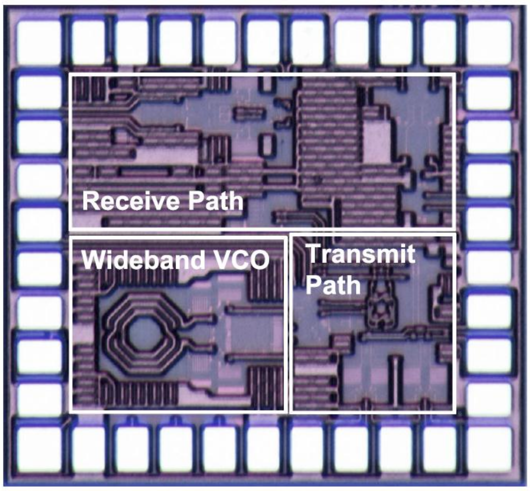


Figure 5-LPS ASIC prototype used in EU IP E-SPONDER, size 1.3 x 1.2 mm²

The accuracy and precision of a system with a custom-designed PLL was simulated in comparison with the PLL employed in the current prototype. The results are plotted in Figure 6 and in Figure 7, and they show the current un-optimized case compared with the results of the custom PLL. Two main issues with the current PLL were discovered and solved:

- Crossing of digital signals between clock domains of different frequencies has been optimized to minimize timing uncertainties and therefore improve timing synchronization between different units. (Clock Domain Issue)
- Glitches in the logic during wideband chirps have been identified, which degrade linearity of the generated chirp. (Integer Glitch Issue)

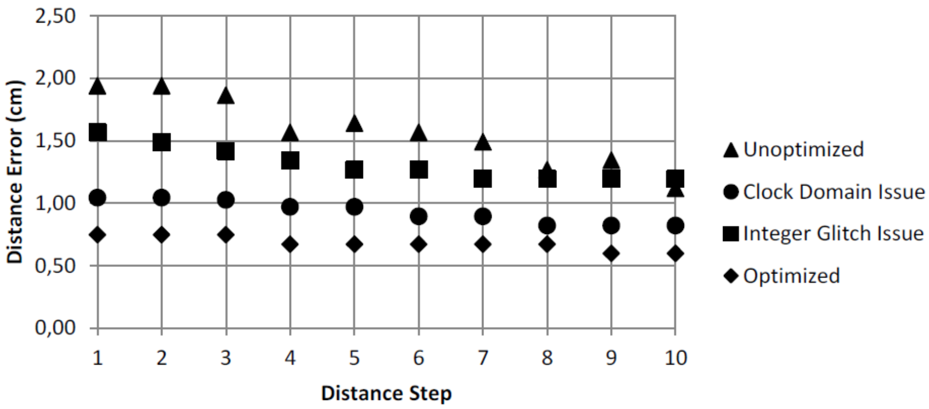


Figure 6- Accuracy simulation results for different distances

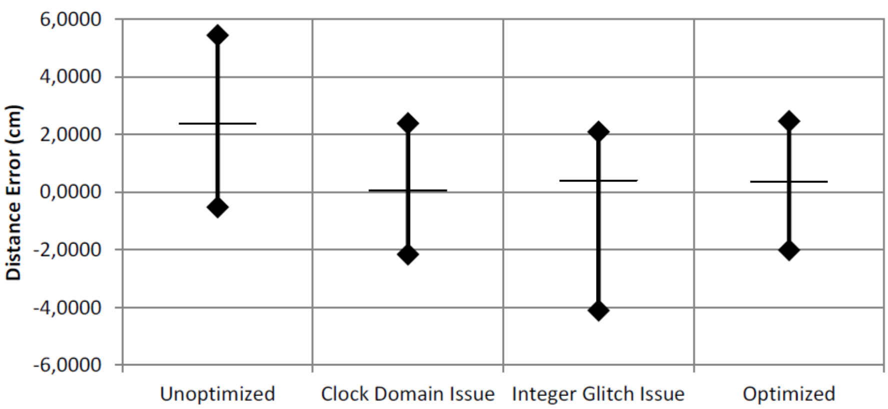


Figure 7-Precision simulation results for different optimizations

It can be observed that the distance error improves by a factor of 2.5 compared to the un-optimized case. Precision is bounded to +/- 2 cm in the optimized case compared to -1/+5.5 cm before. A preliminary layout image of the optimized chip currently in design is presented below in Figure 8. It includes the basic transmit and receive path of the current prototype with added power management function to save power (selectable power down) and the custom integrated PLL. The estimated size is around 2 mm², which is only 0.5 mm² larger than the current version.

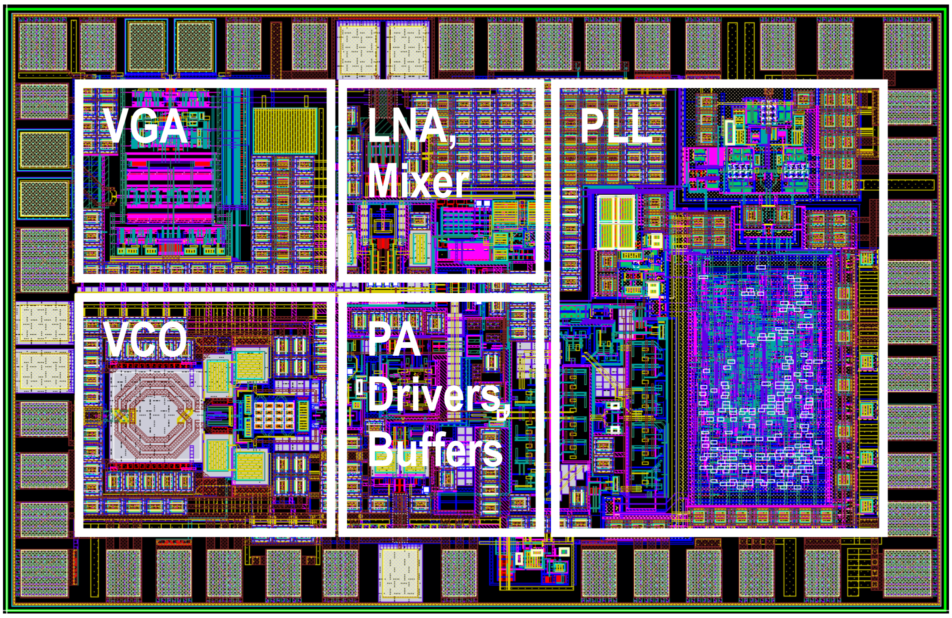


Figure 8-Preliminary layout of improved chip design, size ~1 x 2 mm²

1.1.4. Reference GPS nodes

There are two types of GPS modules that can be utilized in RECONASS as reference. The two types of GPS receiver modules are code-based and carrier phase-based. Real-Time Kinematic (RTK) technique is often implemented with carrier phase-based GPS modules. GPS is a constellation of satellites that orbit the earth twice a day, transmitting precise time and position (latitude, longitude and altitude) information. The complete system consists of 24 satellites and five ground stations to monitor and manage the satellite constellation. The basis of GPS technology is precise time and position information. Using atomic clocks and location data, each satellite continuously broadcasts the time and its position.

Code-based positioning

The traditional positioning technique is based on code-based positioning, because the receiver correlates with and uses the pseudorandom codes transmitted by four or more satellites to determine the ranges to the satellites. From these ranges and knowing where the satellites are, the receiver can establish its position to within a few meters. Code-based receivers are characterized by their low-cost prices. It is planned to use accurate and low-cost GPS modules and their specifications are indicatively presented below, whereas the final specification will be reported within D2.2. The errors that can affect the accuracy of standard GNSS pseudorange determination, that is, the determination of the pseudorange to a single satellite are categorized into certain sources with having typical error ranges. These errors sources and their typical ranges are shown in Table 1 below:

Contributing Source	Error Range
Satellite Clocks	±2 m
Orbit errors	±2.5 m
Ionospheric delays	±5 m
Tropospheric delays	±0.5 m
Receiver noise	±0.3 m
Multipath	±1 m

Table 1-Error sources of GPS and their ranges [15]

Besides the relatively large errors mentioned previously, the following drawbacks exist in low-cost receivers:

- No raw data output or bad accuracy and resolution of raw data (access to NMEA message)
- Low update rate
- Limited connectivity, power supply
- No data recording
- No functionality for DGPS, SBAS, RTK Base or Rover
- Jamming, Spoofing

An example of a candidate hardware which serves as low-cost GPS device that can be used for RECONASS is the LS20033 GPS module which can be purchased for a price under 60 Euro. It has the following features and applications:

Features

- MediaTek high sensitivity chipset
- Support 32-channel GPS
- Fast TTFF at low signal level
- Up to 5 Hz update rate
- Capable of satellite-based augmentation service (SBAS)
- Build-in micro battery to reserve system data for rapid satellite acquisition (not in LS20033)
- LED indicator for GPS fix or not fix (not in LS20033)

Application

- Personal positioning and navigation
- Automotive navigation
- Marine navigation

Error modelling

Intensive research is conducted to characterize the various sources of error that may affect GPS radio signal as it propagates from satellite to receiver. The commonly used error model include both the satellite and receiver's clock synchronization biases from actual GPS system time, delays due to propagation speed retardation as the signal traverses the Earth's atmosphere, multipath interference, antenna phase centre offsets, satellite orbital errors, and receiver noise.

Based on these errors, we can formulate pseudoranges and carrier phase observation models for a single receiver [5]:

$$P_r^s = \rho_r^s - c\tau^s(t) + c\tau_r(t) + M_{r,\rho}^s(t) + \varphi_r^s(t) + d_{trop}^s + d_{ion}^s + E^s + \epsilon_P$$

$$\lambda_{L1}\emptyset_r^s = \rho_r^s - c\tau^s(t) + c\tau_r(t) + M_{r,\emptyset}^s(t) + \varphi_r^s(t) + d_{trop}^s - d_{ion}^s + E^s + B_r^s + \epsilon_\emptyset$$

P_r^s: is the measured pseudorange
ρ_r^s: is the geometrical range
c: is the speed of light
$\tau^s(t)$: Satellite clock bias
τ_r : Receiver clock bias
$M_{r,\rho}^s(t)$: Multi-path effect
d_{trop}^s: Tropospheric delay
d_{ion}^sIonosphere delay
E^s: Satellite orbital error
φ_r^s: Antenna phase center offset
B_r^s: A constant ambiguity term
λ_{L1}: Wavelength of the carrier signal
ϵ: Receiver noise

Those errors can be eliminated by assuming that they will be common in a limited region.

Carrier phase-based positioning

In carrier phase-based positioning the range is measured in units of cycles of the carrier frequency. Using GPS carrier frequency significantly improves the GPS accuracy because it has much higher frequency and therefore more accurate timing. Survey receivers make successful use of both approaches by starting with the C/A code and then move on to measurements based on the carrier frequency for that code. The pseudo random code has a bit rate of about 1 MHz but its carrier frequency has a cycle rate of over a GHz (which is 1000 times faster). At the speed of light the 1.57 GHz GPS signal has a wavelength of roughly twenty centimetres, so the carrier signal can act as a much more accurate reference than the pseudo random code by itself. If we can get to within one percent of perfect phase like we do with code-phase receivers we can get below 1 cm accuracy. A comparison between code and carrier-phase signals is shown in Figure 9.

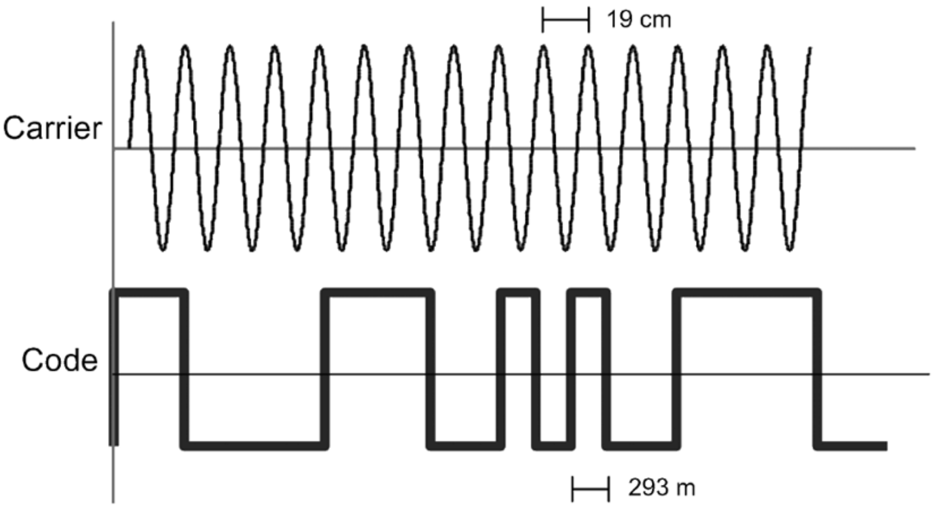


Figure 9-Code and carrier-phase GPS signals (code bits not to scale with carrier wavelength) [4]

Real-Time Kinematic (RTK) based positioning

For many applications such as surveying, higher accuracies are required. Real-Time Kinematic (RTK), a technique that uses carrier-based ranging, provides ranges (and therefore positions) that are orders of magnitude more precise than those available through code-based positioning. Real-time kinematic techniques are complicated. The basic concept is to reduce and remove errors common to a base station and rover pair, as illustrated in Figure 10.

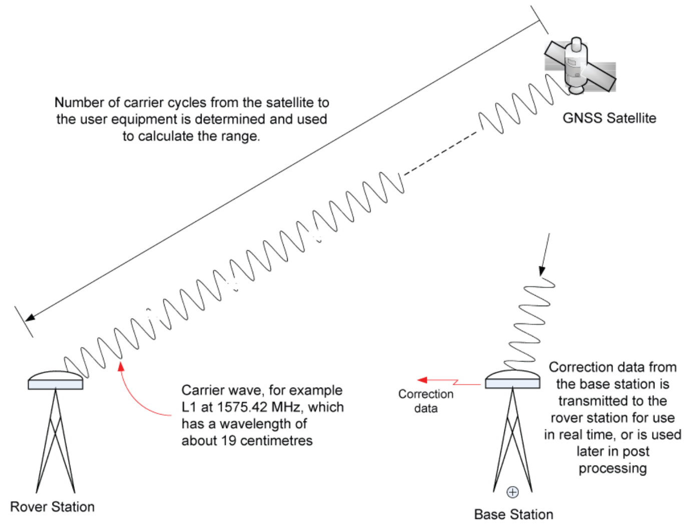


Figure 10-Real-time kinematics [1]

At a very basic conceptual level, the range is calculated by determining the number of carrier cycles between the satellite and the rover station, then multiplying this number by the carrier wavelength. A complicated process

called "*ambiguity resolution*" is needed to determine the number of whole cycles. Rovers determine their position using algorithms that incorporate ambiguity resolution and differential correction. Like DGNSS, the position accuracy achievable by the rover depends on, among other things, its distance from the base station (referred to as the "baseline") and the accuracy of the differential corrections. Corrections are as accurate as the known location of the base station and the quality of the base station's satellite observations. Site selection is important for minimizing environmental effects such as interference and multipath, as is the quality of the base station and rover receivers and antennas.
Due to the expected higher accuracy from the carrier phase-based receivers, they will be the main selected GPS modules for RECONASS. One example for a low-cost carrier phase-based receiver is the LEA-6T [8] from UBLOX. Another example of a candidate hardware which serves as RTK GPS device that can be used for RECONASS is the Piksi GPS module [2] which can be purchased for a price under 900 Euro. It has the following features and applications:

Features

- Centimetre accurate relative positioning (Carrier phase RTK)
- 50 Hz position/velocity/time solutions
- Open-source software & board design
- Low power consumption - 500mW typical
- Small form factor - 53x53mm
- USB and dual UART connectivity
- Integrated patch antenna and external antenna input
- Full-rate raw sample pass-through over USB
- 3-bit, 16.368 MS/s L1 front-end support
- GPS, GLONASS, Galileo and SBAS signals

Applications

- Autonomous vehicle guidance, e.g. formation flight and autonomous landing
- GPS/GNSS research
- Surveying systems

1.1.5. Measures for highly compact LPS

We describe next the measures for making the highly compact LPS. The newly designed chip should have the following features:

- Broadband operation from 2.3-3.1 GHz and 4.9-6.3 GHz (covers two ISM bands)
  - Part of multipath and interference mitigation strategy
  - Resolution enhancement possible to 16.5 cm in worst case reflective scenario (single band operation has up to 130 cm worst case)
- Improved digital synchronization hardware
  - Improved RF signal and time synchronization stability
  - Precision enhancement to up to 2 cm (simulation results)
  - Accuracy enhancement to up to 1 cm (simulation results)

1.1.6. Analysis of the technical specifications

The following items are a list of requirements based on end-user requirements that are relevant to the LPS:

- The sensor network shall be easily switched on with one button (this will be in coordination with other sensors)
- The system shall tolerate power break down for some hours Pass/Fail Statement: At least: 72 hours. This will be supported by power back up system.
- The system shall start automatically after power break down
- The LPS system shall inform about place of damaged sensors and the maintenance measures necessary to ensure functionality.
- Sensor data acquirement and data transmission must be fast enough to allow near real-time damage assessment (Real-time capability)

- Wake-up capability to save power
- Memory for saving history of positioning data
- To be triggered by accelerometers
- Movement of persons inside the building should not cause signal reflections or interfere the line of sight
- If the whole system (sensor nodes and coordinator) moves due to e.g. an earth quake, the LPS should be capable to update the new location of the coordinator and the corresponding tags
- Possible mounting of sensor nodes could be a box inside the wall, with antenna poking out
- Update rate : 1 Hz (Higher update rate are being worked on)
- Power Supply: Power grid connection possible, with backup battery
- 10 cm accuracy, 10 cm resolution
- Coverage for the complete system: 200 m
- Coverage for one room: 30 m
- The system shall provide GIS-ready data. The positions of tags are represented in the world geodetic system WGS84 based on GPS data.
- To be interfaced with accelerometers and other sensors for updating location through dead reckoning
- The system shall tolerate power break down for some hours. (Pass/Fail statement, “at least 48 hours”
- The system must start automatically after power break down
- The system shall send failure messages and maintenance information to a central unit collecting data from different buildings
- The life expectancy of the sensor network/monitoring system shall be >25 years
- Battery powered sensor and communication units shall have battery change intervals of > 2 years
- Sensor units are small enough to be integrated into the building structure during construction
- Maximum sensor unit size shall be 25X50X100 mm *(This might be exceeded, the goal is to come closer to this size)*
- Parts of the sensor network / monitoring system shall be allowed to be connected by cables for power supply and communication
- Conformity with the relevant regulations shall be reached and declared (EC)
- The system shall deliver data and results via WLAN
- The system shall allow to monitor measured or calculated data during an intervention to enhance safety
- The sensor network/monitoring system shall be connected with other monitoring systems (e.g. fire detecting system)
- Resilience in multipath environments shall be met
- Integration into the building structure and antenna design
- Low power consumption to support power life shall be supported
- Enhanced range in reinforced concrete buildings
- Common framework of communication for sensor networks
- Communication gateway must be interoperable to bridge between different types of sensor networks
- Fault tolerance – if sensor nodes fail the communication system must reroute the data paths
- Interoperability: the gateway should be capable to operate different wireless access technologies
- Sensor data acquirement and data transmission must be fast enough to allow near real time damage assessment
- Results of comparable research projects must be monitored to ensure standardized interoperability
- The possibility to install additional position tags for first responder-teams. (This will be possible under certain scenarios)

Based on user requirements we reached the user specifications and we can summarize the important technical specifications that belong to the LPS as:

- Coordinator has wall power supply and supplies nodes on a per-room basis by cable
- Use 12 V lead-gel or lithium-based battery for backup
- Implement wake-up strategies to save battery life
- LPS provides numerical location of every node in WGS84 format

- Physical size of tag estimated 140 x 80 x 27 mm³
- No size specifications for the coordinator, probably similar size, but thicker for battery
- Data transmission by ZigBee or Ethernet (from internal history memory)
- GPS antennas will be placed outside of the building in a position with a clear sky as much as possible
- LPS antennas will be placed inside building
- Accurate reference position is achieved through a differential GPS using few RTK receivers
- below 10 cm accuracy and precision
- Coverage for the complete system: 200 m and coverage for one room: 30 m

1.2. Accurate positioning algorithms and GPS error reduction algorithms

Next, we describe how to reduce errors in low-cost GPS modules based on data from limited number of highly accurate GPS modules. This algorithm will reduce costs by reducing the number of the used expensive accurate GPS units. Theoretically, we need only one accurate GPS reference for the whole building to guide the other low-cost units. For the project we need to deploy large number of low-cost receivers (C/A or carrier phase to reduce costs). We follow a similar approach to the differential GPS operation principle to correct for the errors in the pseudo range measurement. The differential GPS needs a fixed known position of a GNSS receiver, referred to as a “base station”. In our case the base station is determined to a high degree of accuracy using PIKSI RTK GPS receiver. Corrections are sent from the RTK GPS base station to the low-cost receivers. The base station compares the ranges. Differences between the ranges can be attributed to satellite ephemeris and clock errors, but mostly to errors associated with atmospheric delay. Base stations send these errors to other receivers (rovers), which incorporate the corrections into their position calculations. Differential positioning requires a data link between base stations and rovers if corrections need to be applied in real-time, and at least four GNSS satellites in view at both the base station and the rovers. The absolute accuracy of the rover’s computed position will depend on the absolute accuracy of the base station’s position. Since GNSS satellites orbit high above the earth, the propagation paths from the satellites to the base stations and rovers pass through similar atmospheric conditions, as long as the base station and rovers are not too far apart. Differential GNSS works very well with base-station-to-rover separations of up to tens of kilometres and in our case we have more limited spacing.

The use of multiple low-cost carrier phase GPS based receivers for accurate positioning have proven to be a valid approach and with the differential tracking based algorithms, a centimetre-scale tracking accuracy at an update rate of 1 Hz can be reached [5]. The differential tracking algorithms work well for the giving accurate relative positioning, not absolute position, with accuracy clearly below 10 cm. It should be noted that the differential tracking algorithms need at least 5 satellites in view to start working and converge to the accurate solution. The accuracy is dependent upon the baseline distance from reference station to the GPS receiver. It is roughly in the range of 1-5 cm (for baseline <10Km without considering multipath error). If absolute positioning is needed, the relative positioning can be converted to absolute simply by placing the reference module at a stationary known in advance position (This option can be investigated in the implementation phase). Moreover, we can reduce errors in low-cost GPS modules based on data from limited number of highly accurate GPS modules. We will develop algorithms that can improve both local and global positioning systems.

2. STRAIN, ACCELERATION AND TEMPERATURE SENSORS

2.1. Strain sensors

2.1.1. The strain gauge sensors architecture

The strain gauge selected together with the developed signal conditioning circuit for this type of structural health monitoring is a state of the art bespoke pre-wired precision strain gauge, stacked (round carrier) rectangular TEE-Rosette. Rosettes are normally used to compute the value of stress at a particular point. The plotted results as shown in Figure 11 will form a Mohr circle, which gives the value and orientation of principal strains.

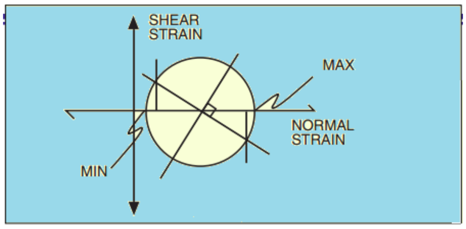


Figure 11-Mohr circle displaying the orientation of the principle strain

The selected TEE-Rosettes strain gauge has two measuring grids laid out in a Cartesian coordinate X-Y Pattern. Different arrangements may be requested to cover most strain measurement applications. The rugged construction and flexibility make these general purpose strain gauges suitable for static and dynamic measurement with a high degree of accuracy. The measuring grid is formed by etching Constantan foil, which is then completely sealed in a carrier medium composed of polyimide film. These strain gauges are pre-wired with either two 3-ft (1 m) leads or three 9-ft (3 m) leads. Standard strain gauges have temperature coefficients matched to steel. The framework of strain gauges will consist of structural nodal attachment of the TEE-Rosettes 5% biaxial strain gauge to the reinforcement bars within the ground floor concrete columns and beams of the structure to be monitored. The sensor will be attached using e.g. TT300 (strain gauge adhesive) cement which is a heat-cured, 2-part epoxy adhesive that can be used to bond polyimide-backed strain gauges for strain measurement up to 200°C (392°F). The sensor will be installed in a known direction from which it is possible to measure compressive or tensile strains that each column or beam may be subjected to as a result of earthquake and/or explosion as shown in Figure 12.

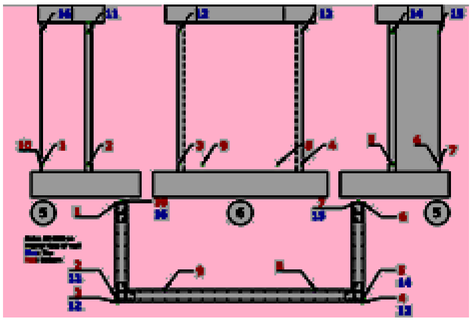


Figure 12-Possible nodal positioning of the strain gauge sensors in the pilot building.

The pre-wired strain gauge, biaxial TEE-Rosette will deliver the measured strain data to the data hub, where they will be collated, converted and subsequently forwarded to the gateway to further establish the necessary strain data exchange channel and process between the database (i.e. PCCDN) from which the client structural algorithm can access to analyse health of the structure post disaster as shown in Figure 13.

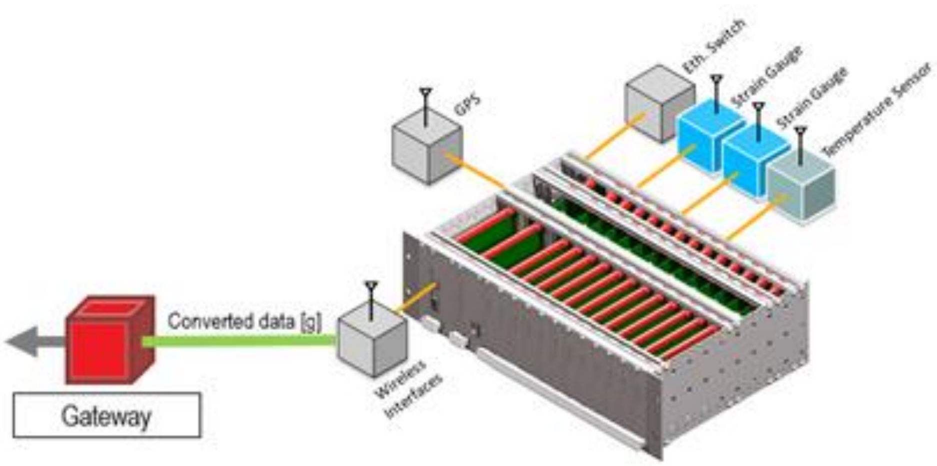


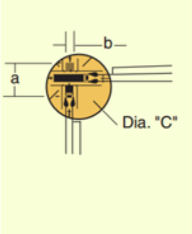
Figure 13-Strain and temperature sensor input and output signal connection.

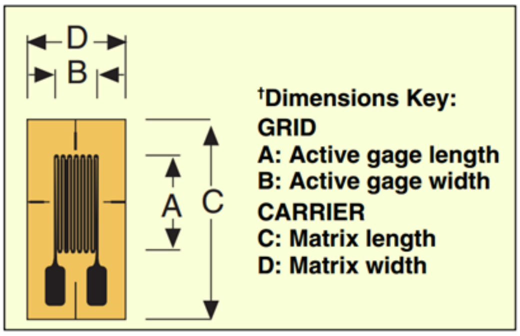
2.1.2. Description of the strain gauge sensors and performance parameters

Framework

The TEE-Rosettes have two measuring grids (X-Y Pattern) forming a metallic strain gauge that consists of a very fine wire or, more commonly, metallic foil arranged in a rosette grid pattern. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction (Figure 14). The cross-sectional area of the grid is minimized to reduce the effect of shear strain and Poisson Strain. The grid is bonded to a thin backing, called the carrier, which is attached directly to the test specimen. Therefore, the strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance. Strain gauges are available commercially with nominal resistance values from 30 to 3,000 Ω, with 120 and 350 Ω being the most common values for the Rosette type.

MODEL NO.	PRICE PER PKG OF 10	NOM. RESISTANCE (Ω)	DIMENSIONS mm (in)† GRID A	GRID B	CARRIER C	CARRIER D	MAX V* (Vrms)	TERMINATION	TEMP COMP.
KFG-3-350-D16-11L3M3S	366	350	3.0 (0.12)	1.3 (0.051)	10.0 (0.39)	—	4	3 wire	STE





Termination
2 Wire: 2 lead wires, 1 m (3') attached
3 Wire: 3 lead wires, 3 m (9') attached
(minimize lead wire resistance effects)

Temperature Compensation
STE Steel 10.8 ppm/C

Figure 14-Pre-Wired Strain Gauges, Biaxial TEE-Rosette

A representative operative circuit for the TEE-Rosette strain gauge configurations, as shown in Figure 14 assumes that the lead wire resistance is negligible. Although ignoring the lead resistance may be beneficial to understanding the fundamentals of strain gauge measurements, doing so in preparation can be a major source of error. As an example we consider the 2-wire connection of a TEE-Rosette strain gauge shown in Figure 15 and we further assume that each lead wire being connected to the strain gauge is 15 m long with lead resistance R_L equal to 1 Ω. As a result, the lead resistance adds 2 Ω of resistance to that arm of the bridge. Also adding an offset error, the lead resistance also desensitizes the output of the bridge.

One can compensate for this error by measuring the lead resistance R_L and accounting for it in the strain calculations. But, a more difficult problem arises from changes in the lead resistance due to temperature fluctuations. Given typical temperature coefficients for copper wire, a slight change in temperature can make a measurement error of several microstrain.

Using a 3-wire connection can eradicate the effects of variable lead wire resistance because the wire resistance affects adjacent legs of the bridge. As seen in Figure 15b, changes in lead wire resistance, R_{L2}, do not alter the ratio of the bridge legs R_3 and R_G. Therefore, any changes in resistance due to temperature cancel out each other.

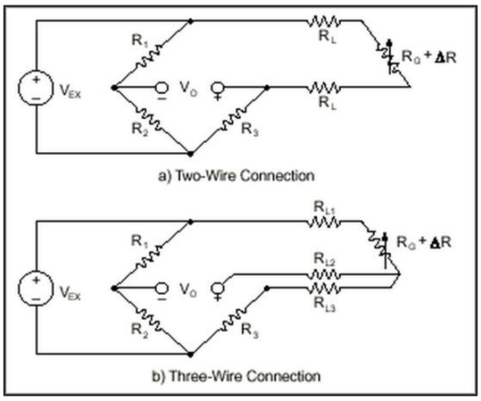


Figure 15-2-Wire and 3-Wire Connections of Quarter-Bridge Circuit

Module description, key performance parameters

The TEE-Rosette specification of the strain gauge is multipurpose gauge that will suits exactly the measurement criteria required for the RECONASS project (see D1.4), but due to the very high measurements of 5% strain (or 50,000 µstrain) the gauge will be reusable post any disaster as shown in Table 2.

	KFG SERIES
Foil strain gages are constructed by embedding a foil measuring element into a carrier. Foil measuring grid Carrier Substrate thickness Cover thickness Connection dimensions in (mm) [in]	Constantan foil 6 µm thick Kapton 15 µm 9 µm 27 AWG strand polyvinyl insulation (1 x 2) [.04 x .08]
Nominal resistance Resistance tolerance per package Gage factor (µΩ/µ/µΩ) (actual value printed on each package) Gage factor tolerance per package	120 ±0.4 ohms 03% 2.10 ±10% 1.0%
Thermal Properties Reference temperature Service temperature: Static measurements Dynamic measurements Temperature characteristics: Steel Aluminum Uncompensated Temperature compensated range Tolerance of temp. compensation	 23°C/73°F -20 to 100°C (-4 to 212°F) -20 to 100°C (-4 to 212°F) 10.8 ppm°C (6 ppm°F) — — 10 to 80°C (50 to 176°F) 1 ppm°C (0.5 ppm°F)
Mechanical Properties Maximum strain Hysteresis Fatigue (at ±1500 µϵ) Smallest bending radius Transverse sensitivity	 5% or 50,000 µϵ Negligible > 10,000,000 cycles 3 mm (⅛ inch) Stated on each package

Table 2-Tee-Rosette strain gauge specifications

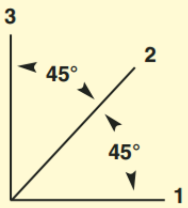
Strain analysis

The stress-strain relations associated with two principal strains (ϵ_1 and ϵ_2) and principal stresses σ_1 and σ_2 are as follows:

$$\epsilon_1 = \frac{\sigma_1}{E} - \frac{\vartheta \sigma_2}{E}$$

$$\epsilon_2 = \frac{\sigma_2}{E} - \frac{\vartheta \sigma_1}{E}$$

Stress-strain relations for a 45° Rosette



$$\epsilon_{p,q} = \frac{1}{2}\left[\epsilon_1 + \epsilon_3 \pm \sqrt{(\epsilon_1 - \epsilon_3)^2 + (2\epsilon_2 - \epsilon_1 - \epsilon_3)^2} \right]$$

$$\sigma_{p,q} = \frac{E}{2}\left[\frac{\epsilon_1 + \epsilon_3}{1 - \nu} \pm \frac{1}{1 + \nu} \sqrt{(\epsilon_1 - \epsilon_3)^2 + (2\epsilon_2 - \epsilon_1 - \epsilon_3)^2} \right]$$

$$\theta_{p,q} = \frac{1}{2} \text{TAN}^{-1} \frac{2\epsilon_2 - \epsilon_1 - \epsilon_3}{\epsilon_1 - \epsilon_3}$$

WHERE:

$\epsilon p,q$ = Principal strains

$\sigma p,q$ = Principal stresses

$\theta p,q$ = the acute angle from the axis of gage 1 to the nearest principal axis. When positive, the direction is the same as that of the gage numbering and, when negative, opposite.

2.2. Acceleration sensors

2.2.1. The accelerometer architecture

The accelerometers developed by GeoSIG are state of the art structural monitoring accelerometers, utilizing MEMS sensor cells. The network of accelerometers will consist of 3 accelerometers per floor as shown in Figure 16. Two accelerometers will be placed in diagonal corners of the floor, one being a single axis accelerometer and the other being a dual axis accelerometer. The third accelerometer will be placed in the largest span of the floor. The sensors will be installed in a known orientation with respect to both the building and north-south-east-west. Having a known orientation it is possible to analyse the behaviour of the building and gain insight into important structural behaviour such as inter-story drift due to lateral and shear forces and ground motion due to earthquakes. The accelerometers also allow monitoring the structures frequency response which can help detect damage to the structure.

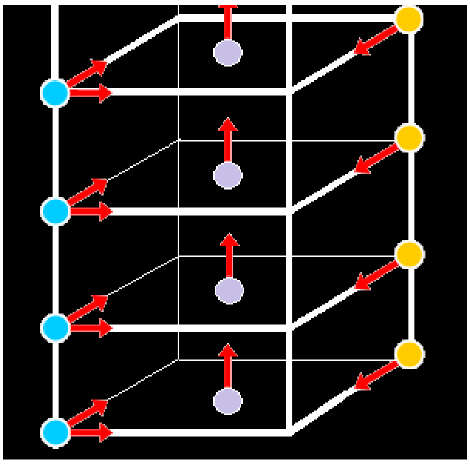


Figure 16-Suggested placement of accelerometers in test building.

The accelerometers will provide the measured acceleration data to the data hub, which will collect and convert it and forward it to the gateway which in turn will provide it to a database accessible to the algorithm analysing the structure as shown in Figure 17.

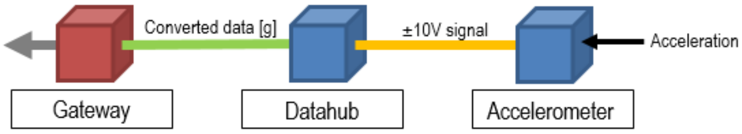


Figure 17-Accelerometer overview.

2.2.2. Description of the accelerometers and performance parameters

Overview

The accelerometers will be based on MEMS sensor cells and will be specially suited for measuring low frequency acceleration as typically observed during earthquakes. The rough functionality of the sensor circuit is sketched in Figure 18. The Analogue output signal of the sensor cell will be low pass filtered to remove unwanted high-frequency noise before the signal is calibrated and scaled and passed on to the output. The sensor will be provided with +12VDC for power and additionally has circuitry which allows a host (the data hub) to force the sensor into a self-test mode.

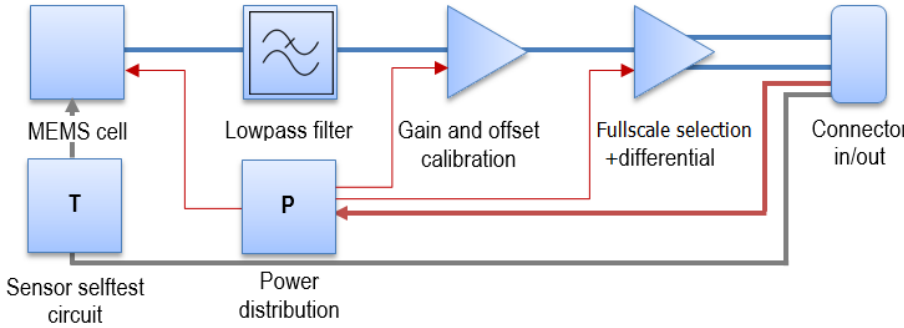


Figure 18-Conceptual diagram of accelerometer circuit.

Performance and specifications

The specifications of the accelerometers are designed, not only to match exactly the requirements in the RECONASS project, but also to match most international codes and requirements for structural monitoring. The specifications are listed in Table 3.

Parameter	Specification
Full scale input	±5g
Full scale output	±10V
Dynamic range	≥ 87dB[1]
Bandwidth	DC-100Hz
Noise	< 150µg on any axis
Operation	Constant
Power Consumption	≤ 1 Watt
Power source	Host delivers power +12V
Backup power source	Host delivers back-up power
Self-test	Force by host

Table 3-Accelerometer specifications

Multiple parallel cells

Due to the relatively low cost of MEMS accelerometers it is a fairly cost effective option to use multiple cells in parallel to improve the overall noise performance of the measurement. The general lower noise levels are at the cost of a higher 1/f noise, and so a compromise is made to balance the two. The expected noise level for the specific sensor cell in use can be calculated as follows:

$$Noise = 50\ \mu g/\sqrt{(Hz)}\ *\ \sqrt{(BW[Hz])}\ *\ 1/\sqrt{(n\_cells)}$$

[1] Has been corrected from 95dB in specifications (see D1.4) to 87dB to correspond with the noise requirement of <150µg.

The calculation assumes 50Hz bandwidth and one sensor cell:

$$50\ \mu g/\surd(Hz)\ *\ \surd(50Hz)\ *\ 1/\surd(1)\ =\ 354\ \mu g$$

By increasing the amount of cells from one to four, it can be seen that the noise level is halved:

$$50\ \mu g/\surd(Hz)\ *\ \surd(50Hz)\ *\ 1/\surd(4)\ =\ 177\ \mu g$$

By increasing further from 4 to 16 cells the noise level is halved again.

$$50\ \mu g/\surd(Hz)\ *\ \surd(50Hz)\ *\ 1/\surd(16)\ =\ 88\ \mu g$$

The theoretical dynamic range (DR) can be calculated by the formula:

$$DR = 20 * LOG_{10}((Full\_scale * 1/\surd(2))/noise\_level)$$

This applied to the 4-cell option and the 16-cell option gives the theoretical dynamic ranges which are listed in Table 4:

Sensor	Dynamic Range
AC-43-4	86dB
AC-43-16	92dB

Table 4-Dynamic range of 4-cell sensor and 16-cell sensor

1/f noise

In the specific application of structural monitoring, it is important to have a good DC response, and so 1/f noise becomes critical. A trade-off has to be made between 1/f noise and the dynamic range of the sensor – a topic which will be investigated further during the continued development.

Physical dimensions

The accelerometer is housed in GeoSIG Ltd standard cast aluminium alloy housing. Dimensions and technical drawing is included in Figure 19. The housing is still subject to testing near explosions. It is expected that specially designed explosion proof enclosure will be needed.

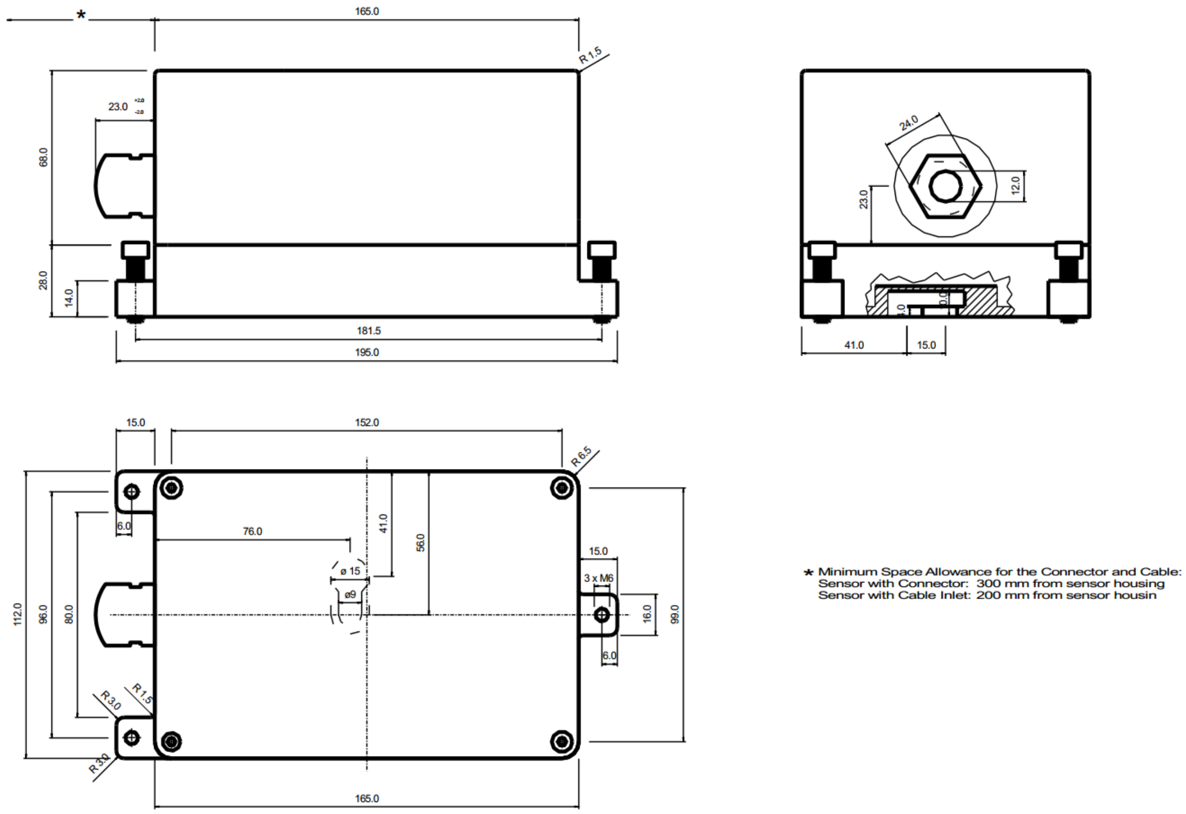


Figure 19-GeoSIG Ltd standard sensor housing

2.3. Temperature sensors

2.3.1. The temperature sensors architecture

The temperature sensor selected for this type of Structural Health Monitoring application within the RECONAS project is a state of the art CTL series. The specific temperature sensor is a noncontact infrared one with laser crosshairs for accurate measurement as shown in Figure 20. They calculate the surface temperature based on the emitted infrared energy of objects. An integrated double laser aiming marks the actual measurement spot location and spot size at any distance on the object surface. The sensor housing of the CTL sensor is made of stainless steel (IP 65/ NEMA-4 rating) – the sensor electronics is placed in a separate box made of die casting zinc.

Infrared detectors are very accurate and are considered as none invasive method of measuring temperature even in most hostile environments. The accuracy of the detection is based on the ability of getting the relevant parameters correctly. Nominally these are, ε emissivity, φ reflection, τ transmissivity, where:

$$\varepsilon + \varphi + \tau = 1$$

Figure 20-Infrared Sensor with Laser Aiming

The sensors will be installed in a known agreed orientation. Having a known orientation helps to locate the sensor in a position where it is most desirable to measure the high temperatures in case of a disaster and most protective position with regards to protection of the sensor from local environmental conditions. For such positions, it is recommended that the sensor is not near the window or facing a window. Figure 21 shows the installation of infrared sensor with Laser aiming.

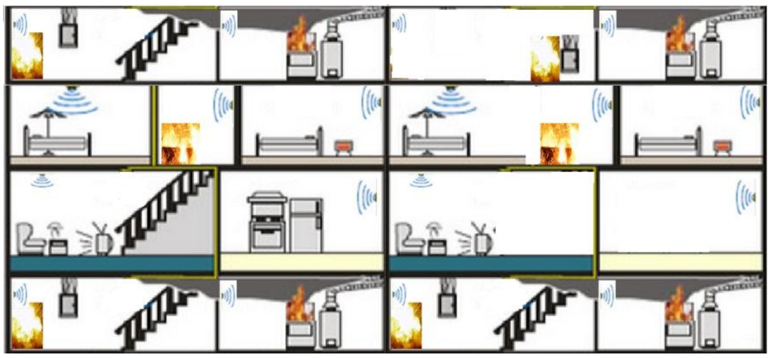


Figure 21- Installation of infrared sensors with Laser aiming

Similar to strain and accelerometer sensors, the infrared sensor will deliver the measured temperature data to the data hub, where they will be collated, converted and subsequently forwarded to the gateway to further establish the necessary temperature data exchange channel and process between the database (i.e. PCCDN) from which the client structural algorithm can access to analyse health of the structure post disaster (see strain and accelerometer block diagram). Figure 22 shows different spectral emissivity of some materials.

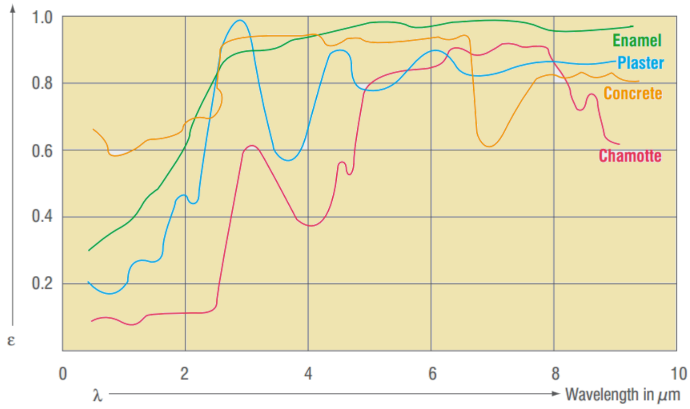


Figure 22-Spectral emissivity of some materials

2.3.2. Description of the temperature sensors and performance parameters

Figure 23 shows the general construction of the selected infrared thermometer. Together with the input optics the emitted object radiation is focused onto an infrared detector. The detector generates a corresponding electrical signal which then is amplified and may be used for further processing. Digital signal processing converts the signal into an output value proportional to the surface temperature. The temperature result is either shown on a display or may be used as Analogue signal for further processing. In order to recompense for the influences from the background temperature a second detector catches the temperature of the measuring device and of his optical channel, respectively. Therefore, the temperature of the measuring object is mainly generated in three steps

1. Transformation of the received infrared radiation into an electrical signal
2. Compensation of background radiation from thermometer and object
3. Linearization and output of temperature information.

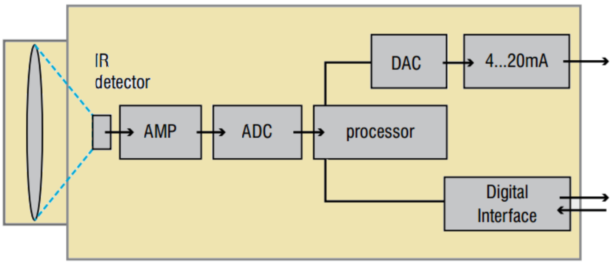


Figure 23-Block diagram of an infrared thermometer

Additionally, to provide a temperature value, the thermometers also support linear outputs such as 0/4-20 mA, 0-10 V and thermocouple elements which allow an easy connection to control systems of the process managements Furthermore, the most of the presently used infrared thermometers offer digital interfaces (USB, RS232, RS485) for further digital signal processing and in order to be able to have access to the device parameters.

Performance and specifications

The specifications of the infrared thermometer are very versatile and designed, not only to match exactly the requirements in the RECONASS project (see D1.4), but also to match many applications where non-contact and accurate in temperature readings are required .The specifications are listed in Table 5, Table 6 and Table 7.

Technical Data

	Sensor	Controller
Environmental rating	IP 65 (NEMA-4)	IP 65 (NEMA-4
Ambient temperature 1)	-20...85 °C	0...85 °C
Storage temperature	-40...85 °C	-40...85 °C
Relative humidity	10...95 %, non condensing	10...95 %, non condensing
Material	stainless steel	die casting zinc
Dimensions	100 mm x 50 mm, M48x1,5	89 mm x 70 mm x 30 mm
Weight	600 g	420 g
Cable length	3 m (Standard), 8 m, 15 m	
Cable diameter	5 mm	
Ambient temperature cable	105 °C max. [High temperature cable (optional): 180 °C]	
Vibration	IEC 68-2-6: 3G, 11 – 200 Hz, any axis	
Shock	IEC 68-2-27: 50G, 11 ms, any axis	
EMC	2004/108/EC	

Table 5-General specification

Power Supply	8–36 VDC
Current draw	max. 160 mA
Aiming laser	635 nm, 1 mW, On/ Off via programming keys or software
Outputs/ analog Channel 1 Channel 2 (L/ LF/ G5)	 selectable: 0/ 4–20 mA, 0–5/ 10 V, thermocouple (J or K) or alarm output (Signal source: object temperature) Sensor temperature [-20...180 °C] as 0–5 V or 0–10 V output or alarm output (Signal source switchable to object temperature or controller temperature if used as alarm output)
Alarm output	Open collector output at Pin AL2 [24 V/ 50 mA]
Output impedances mA mV Thermocouple	 max. loop resistance 500 Ω (at 8-36 VDC), min. 100 KΩ load impedance 20 Ω
Digital interfaces	USB, RS232, RS485, CAN, Profibus DP, Ethernet (optional plug-in modules)
Relay outputs	2 x 60 VDC/ 42 VAC_{RMS}, 0.4 A; optically isolated (optional plug-in module)
Functional inputs	F1-F3; software programmable for the following functions: • external emissivity adjustment, • ambient temperature compensation, • trigger (reset of hold functions)

Table 6-Electrical specification

	CTL	CTLF
Temperature range (scalable)	-50...975 °C	-50...975 °C
Spectral range	8...14 µm	8...14 µm
Optical resolution	75:1	50:1
System accuracy [1) 2)]	±1 °C or ±1 % [3)]	±1.5 °C or ±1.5 % [4)]
Repeatability [1) 2)]	±0.5 °C or ±0,5 % [3)]	±1 °C or ±1 % [4)]
Temperature resolution (NETD)	0.1 °C [3)]	0.5 °C [4)]
Response time (90 % signal)	120 ms	9 ms
Warm-up time	10 min	10 min
Emissivity/ Gain	0.100…1.100 (adjustable via programming keys or software)	
Transmissivity	0.100…1.000 (adjustable via programming keys or software)	
Signal processing	Average, peak hold, valley hold (adjustable via programming keys or software)	
Software	optional	

Table 7-Measurement specification

Physical dimensions and mounting arrangements are shown in Figure 24.

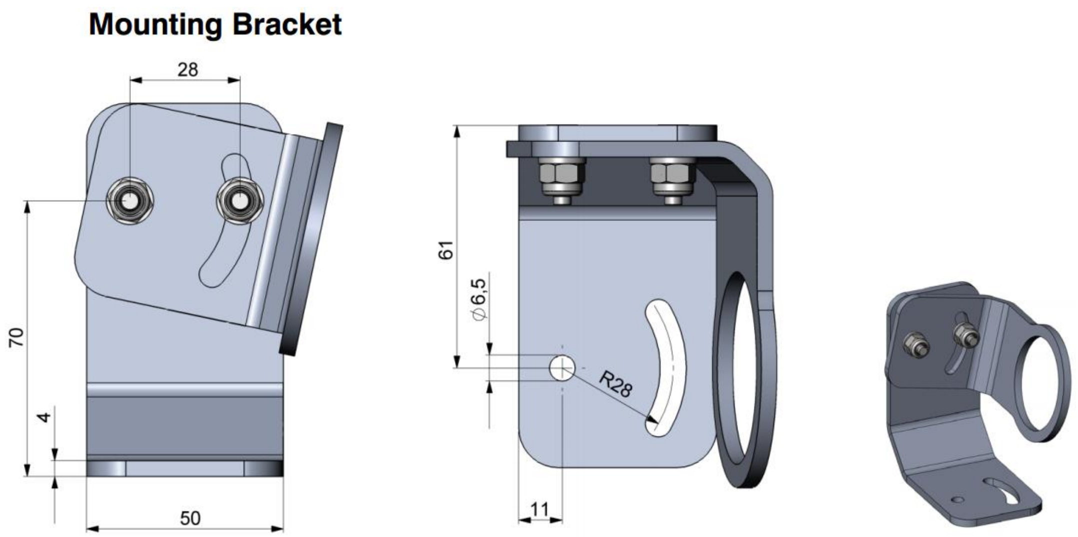


Figure 24-Mounting bracket

3. THE COMMUNICATION MODULE

The RECONASS Communication Module refers to the overall means of communication and interfaces deployed in order to effectively receive data from the sensors' ecosystem and subsequently convey them to the PPCDN tool where the structural/non-structural assessment will take place.

As specified in D1.4, the RECONASS Communication Module will include both hardware and software deployments for enabling on one hand the physical transmission of data utilising common interfaces and protocols and on the other hand to achieve functionalities such as network management and routing along with data aggregation, formatting and classification.

D2.1 is on the LPS and sensor node system architecture; in that sense in the current deliverable from a communication point of view the focus is given on the interfaces shared among the Communication Module, the Local Area Network and the Sensor Network as a result of the work performed within T2.3 so far. To this scope we capitalise on the effort performed in D1.4 with respect to the Communication Module and an extension is provided herein, zooming into the various interfaces and the network considerations where in one end there is the communication module and on the other end we consider the underlying sensing device. The descriptions that follow provide a refinement of the specified interfaces in D1.4 towards the ultimate implementation of a multi standard communication module- gateway.

The following artistic impression of the communication module, shown in Figure 25, coupled with the underlying networks and sensing devices provide us a better insight on the interfaces to be further described. The number indicators are used to specify the interfaces to be further analysed within this document.

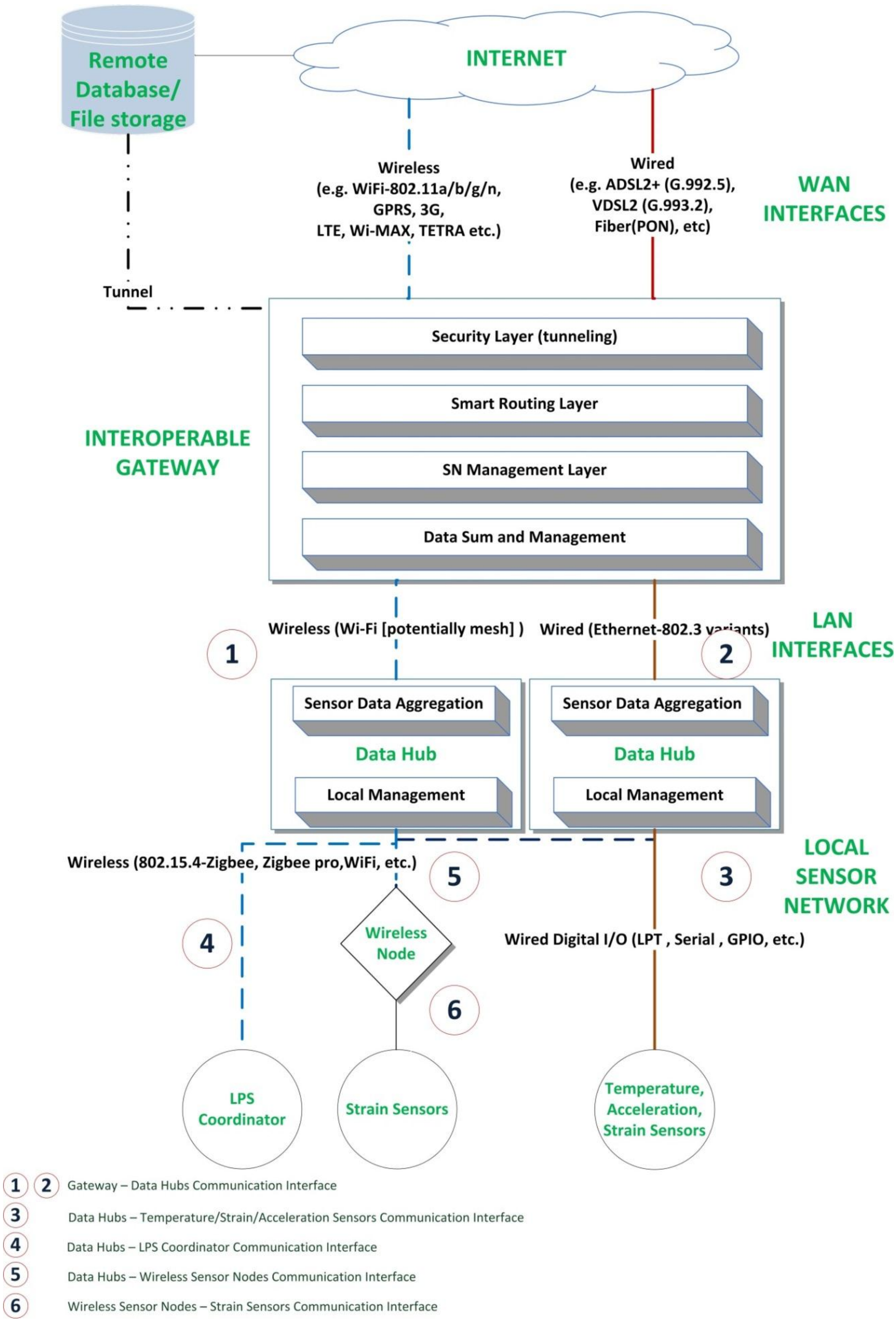


Figure 25-The communication module high level architecture

3.1. Gateway – Data Hubs Interface

The gateway-data hubs interface is responsible for retrieving all sensor data from the local aggregators i.e. the data hubs. To this scope there will be deployed both wireless and wired interfaces in order for the communications to remain functional at all times.

The wireless interface will be a traditional 802.11 a/g/g/n dual band wireless module that also supports Wi-Fi mesh features such as WDS, 802.11s extension and VLAN to SSID mapping. The standard 802.11 a/b/g/n interface will support both interior and exterior gateway routing protocols. For the former case the candidates include OSPF and EIGRP whilst in the former case we will consider EGP. Especially for the mesh functionality BATMAN and OLSR apart from the built in HWMP will be also considered. Table 8 gives a comparison of the different forms of IEEE 802.11 [13].

	IEEE 802.11a	IEEE 802.11b	IEEE 802.11g	IEEE 802.11n
Frequency band	5.7 GHz	2.4 GHz	2.4 GHz	2.4 / 5 GHz
Average Theoretical speed	54 Mbps	11 Mbps	54 Mbps	600 Mbps
Modulation	OFDM	CCK modulated with QPSK	DSSS, CCK, OFDM	OFDM
Channel bandwidth	20 MHz	20 MHz	20 MHz	20 / 40 MHz
Coverage radius	35 m	38 m	38 m	75 m
Unlicensed spectrum	Yes (it depends on countries)	Yes	Yes	Yes (it depends on countries)
Radio Interference	Low	High	High	Low
Introduction cost	Medium- Low	Low	Low	High-medium
Device cost	Medium-Low	Low	Low	Medium
Mobility	Yes	Yes	Yes	Yes
Current use	Medium	High	High	High
Security	Medium	Medium	Medium	High

Table 8-IEEE 802.11 a/b/g/n technology comparison

From a network topology point of view for the traditional 802.11 a/g/g/n dual band wireless module it is expected that the Gateway –Data hubs sub network will be connected in a tree topology (mainly star and partially line especially among the data hubs). Utilising this topology ensures that star and bus topologies can be implemented and mixed under all circumstances adding at the same time a high degree of expandability for the overall network. In such a way, also, the network can be easily segmented and subsequently managed and maintained allowing error detection and possibly correction.

Due to the dynamic changes expected in the case of disasters mesh functionality is also put onto the communications table giving an extra robustness attribute and in parallel eliminating single points of failure. Since in real-life communication conditions several network topologies co-exist, effort will be dedicated on the implementation of specialised software (managed from the gateway) that allows such transitions when crisis occurs.

According to the IEEE 802.11s specifications [6] Wi-Fi mesh devices operate in ad-hoc mode and have mesh routing capabilities.

Wi-Fi mesh networks contain three types of devices:

- Mesh access point: A mesh access point is a traditional access point augmented with mesh functionality providing backhaul connection services for the wireless mesh network and access services for mesh clients.
- Mesh Router: A mesh router (MP) is used to discover neighbouring nodes and keep track of them. Also a mesh router can discover nodes that are not in its range. A mesh router supports the below protocols.

  - Peer Link Management protocol (Communication with neighbours nodes)
  - Hybrid Wireless Mesh Protocol (Communication with nodes out of range – further than one hop)
- Mesh Portal: A mesh portal is a mesh access point which acts like as a gateway for the mesh network. It provides connectivity to other networks.

In wireless mesh the following types of routing protocols are utilised:
- Proactive-The proactive routing protocol maintains routes before a route is needed.
- Reactive-A reactive routing protocol finds a route only when a node wants to communicate with another.
- Hybrid-The hybrid protocol combines the features of proactive and reactive protocols. Some routes are maintained proactively while others are created on demand.
- The Hybrid Wireless Mesh Protocol is the default routing protocol for IEEE 802.11s WLAN mesh networking. It is used for path selection which is necessary in order to find a “route” to a node which is not in the range (one hop) of the mesh point. There are two main parts of HWMP, a proactive portion which is basically a tree-based hierarchical routing protocol, and an on-demand portion, which is a modification of Ad-hoc On Demand Vector (AODV). The modification of AODV is named radio metric - AODV. While AODV works on layer 3 with Internet Protocol (IP) addresses and uses the hop count as a routing metric, RM - AODV is redesigned to use media access control (MAC) addresses and a radio - aware path selection metric for path selection at the data link.

Further to the above, in our proposed topology wireless interfaces will act as edge access points and must support VLAN to SSID mapping. This characteristic will permit to the wireless network to be divided in VLAN sections that can be easily managed and maintained having in parallel different level of security and authorization.

The wired interface consists of 802.3 variants especially the 802.3u and 802.3ac. These interfaces will enable the wired interconnection of all data hubs again in a tree topology. The gateway will utilise mainly star topology to connect to the data hubs, however, some of the data hubs will be also connected to each other (line) in order to provide an additional degree of path redundancy, ensuring that the information from the sensors even in disaster circumstances will reach the final destination i.e. the gateway. This interface will be supported also by an Ethernet Gigabit customisable switch with 802.1Q and 802.1p QoS support in order for the overall tree topology to be implemented (mainly star for the connection of gateway and data and secondarily line among data hubs to increase redundancy). All data hubs are connected to the switch and the switch’s uplink port is connected to the gateway. Through the use of such a switch the network will be separated in broadcast domains allowing future network extensions as well.

In regards to the network design, the final implementation will take place in a building made of reinforced concrete with (full scale dimensions) of 12m x 5m x 7.5m (length x width x height). Additionally the slabs and the load bearing walls are envisioned to be 0.15 m thick. From the previous we derive that each floor’s surface area is approximately $60m^2$ and the total volume $450m^3$. In terms of network devices, it is foreseen from the DoW the usage of 1 gateway (a switch is to be included as a core component of the gateway) and 17 data hubs.
The total amount of data hubs and their exact positions within the pilot structure will be defined by taking into account the exact quantities and positions of the sensors to be used and their respective data rates as well as their communication interfaces along with their core performance properties (coverage, throughput, etc.). It is expected the data hubs will act as both an intermediate communication path to the gateway as well as a redundant solution to the overall network topology being interconnected to more than one sensor networks. After estimating the quantities of the sensors, their exact positions, the communication interfaces and the data rates required the final network design will be produced balancing the various inputs towards a resilient, robust and redundant local area and sensor network. Figure 26 presents a network design that includes the topologies mentioned above.

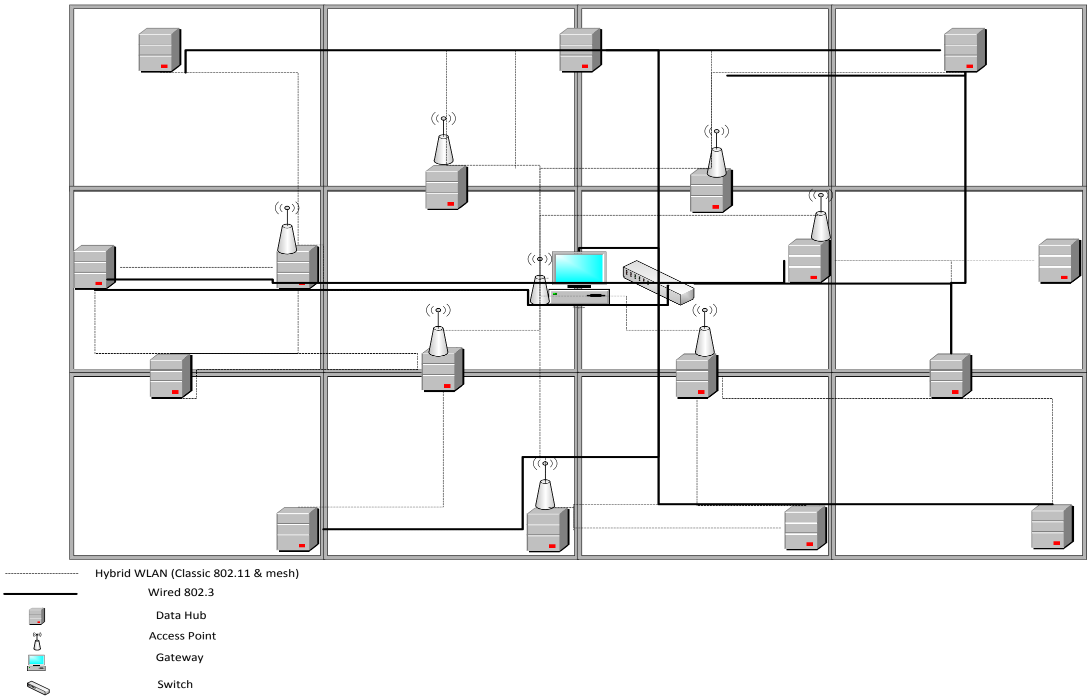


Figure 26-Indicative network design gateway – data hubs

The data hubs capture all sensors' data and subsequently forward them to the gateway utilising the Miniseed format. In that sense all sensors' data are categorised under the topics/headers that the Miniseed format specifies. The format includes recorded data, recorded event data and recorded triggers. Subsequently the gateway translates the Miniseed format to an appropriate protocol that allows utilisation of Sensor Observation Service for the PCCDN tool that is ultimately receiving the sensors' readings and functions.

3.2. Data Hub – Sensor Interfaces

The data hubs will have three types of interfaces to external sensors as shown in Figure 27. The first type is 6 Analogue input channels featuring a 24bit Analogue-to-digital converter (ADC) with a 250Hz 4-pole Butterworth low pass filter between input and ADC. The second type is a digital input, which will communicate with temperature sensors and strain gauges. The interface and protocol is to be finally defined between the partners. The current suggestion is MODBUS over RS485. The last interface is a ZigBee Pro interface, which will be used to communicate with the LPS coordinators and selected strain gauges. Here the protocol is also still to be defined. The current suggestion is MODBUS.

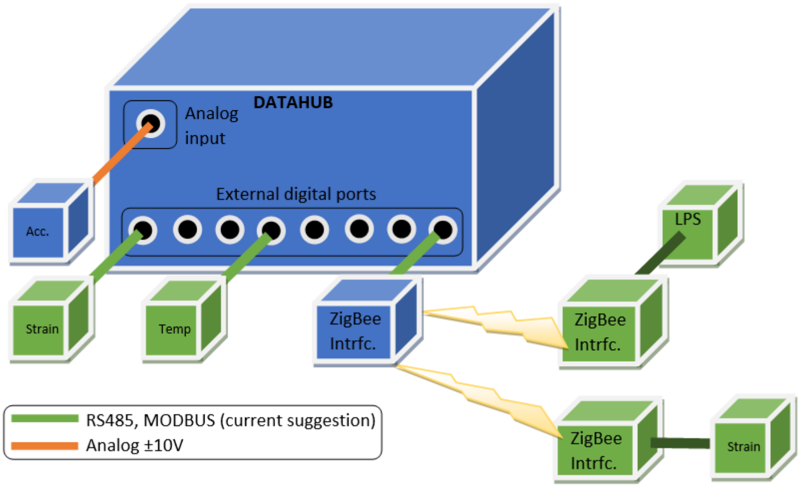


Figure 27-Visualization of data hub to sensor interface.

3.2.1. LPS interface description

Interface: ZigBee Pro interface
Protocol: TBA. Being considered is currently MODBUS and GSBU (GeoSIG + Bergen university protocol).
The LPS coordinators will communicate with the data hub using ZigBee Pro. The data can be accumulated and sent in bundles, each bundle arriving with a number of data points, a start date and start time (precise to milliseconds) for that bundle of data points as well as information about sampling rate, time unit, data unit and sensor ID/name.

Data which need to be transferred from the sensor system to the data hub is:

- Sensor ID/NAME
- Sampling rate used
- Start date (for example: 14.10.2014)
- Start time (for example: 11:58:31.600)
- Time unit (seconds)
- Measurement unit (g, uStrain, mm/s..)
- Measured data

The protocol will be defined bilaterally further into the development. To support self-test functionality, the sensor system must be able to accept an incoming request for a self-test, and be able transmit the result back to the data hub. The data hubs will be connected with the LPS coordinators utilising mainly 802.15 variants. The main technology to be used will be 802.15.4-ZigBee (Pro) however in case that site specific design reveals coverage or throughput blind spots it might be needed to utilise Wi-Fi technology as a supplementary means of transferring data. In order to have a first estimation of the amount of tags and data rates required we provide herein an indicative table of the sensors' properties as shown in Table 9 and Table 10.

	LPS tags
Quantity	54 (+12 if we consider placement on slabs)
Refresh rate	1 Hz
Data size	~ 50 bytes per tag
Data format (conversion)	Details of the preliminary LPS data format are given below

Table 9-Needed quantity of LPS tags

802.15.4 – ZigBee (Pro)				
Frequency Band	**Bit Rate**	**Channels**	**Range**	**Latency**
868/915 MHz	20/40 Kbps	1/10	10/20m (1mW)	<15ms
2.4 GHz	250 Kbps	16	Up to 100m (>1mW)	<15ms

Table 10-Usable frequencies in LPS for communications between tags

LPS data format:
The data format of the LPS tag positions for the interface between the coordinators and the data hubs has to be specified. Since every coordinator connects to a variable number of tags *n*, a list of positions in WGS84 will be created as a text line by the coordinator. Each tag gets a unique identification (ID) for this purpose. The format specification is as follows:

```
<(tag_id_1, time_stamp_1, latitude_1, longitude_1, altitude_1, misc_1);
(tag_id_2, time_stamp_2, latitude_2, longitude_2, altitude_2, misc_2); …
(tag_id_n, time_stamp_n, latitude_n, longitude_n, altitude_n, misc_n)>
```

An example for 3 tags is given below:

```
<(0001, 14022015-12:34:56, 43.356704, 5.322144, 150.000000, 'degrees');
(0002, 14022015-12:34:56, 43.356717, 5.322147, 150.000000, 'degrees');
```

```
(0003, 14022015-12:34:56, 43.356729, 5.322149, 0.000000, 'degrees')>
```

Since the text string can be easily extended by adding more comma-separated information, the misc part can be iterated multiple times and can contain additional information, such as the unit of the measured values (in case of latitude and longitude it is degrees, in case of altitude it is meters). In this manner, the format can be extended in the future to accommodate further requirements, which arise during the design period.

3.2.2. Data Hubs – Temperature/Strain/Acceleration sensors Interface

The data hubs will retrieve sensor information from temperature, acceleration and strain sensors utilising wired and wireless interfaces (i.e. data hub-temperature sensors are wired, data hubs-accelerometers are wired, data hubs-strain sensors are both mainly wirelessly and secondarily wired). The sensors that maintain a wired interface will be connected either through parallel ports, serial ports or general purpose input/output ports. In order to have a first estimation of the amount of sensors and data rates required we provide herein an indicative table of the sensors' properties as shown in Table 11.

	Acceleration sensors	Temperature sensors	Strain sensors
Quantity	~20	~6	~24
Refresh rate	100 Hz	100 Hz	100 Hz
Data size	Data hub at 100SPS: ~2.5MByte / hour / 3 channels Data hub at 200SPS: ~5MByte / hour / 3 channels	Data hub at 100SPS: ~3 MByte / hour / 3 channels Data hub at 200SPS: ~5MByte / hour / 3 channels	Data hub at 100SPS: ~2 MByte / hour / 3 channels Data hub at 200SPS: ~5MByte / hour / 3 channels
Data format (conversion)	Acceleration data converted to unit [g] by Data hub.	Degree Celsius	Micro strain

Table 11-Quantity of needed sensors

3.2.3. Strain sensors interface description

Interface 1: ZigBee Pro interface described previously with the corresponding protocol.
Data which need to be transferred from the sensor to the data hub using ZigBee Pro is:

- Sensor ID/NAME
- Sampling rate used
- Start date (for example: 14.10.2014)
- Start time (for example: 11:58:31.600)
- Time unit (seconds)
- Measurement unit (g, uStrain, mm/s..)
- Measured data

The protocol is to be defined bilaterally further into the development. To support self-test functionality, the sensor system must be able to accept an incoming request for a self-test, and be able transmit the result back to the data hub.

Interface 2: Analogue interface (±10V differential)
In case of an Analogue signal, the data hub will accept a ±10V differential signal. The Analogue frontend contains a 4 pole 250Hz Butterworth low pass filter. For all Analogue signals, time stamping is provided by the Data hub. If the sensor supports self-test functionality, this functionality will be requested by sending a 10V pulse to the sensor.

Interface 3: wired digital signal interface (to be defined. Options being considered include RS232, RS485, USB, Ethernet, etc.)
Protocol: (to be defined further into the development process). Being considered is currently MODBUS and GSBU (GeoSIG + Bergen university protocol).
The strain sensors will communicate with the data hub using digital signals on a wired connection. The data can be accumulated and sent in bundles, each bundle arriving with a number of data points, a start date and start time (precise to milliseconds) for that bundle of data points as well as information about sampling rate, time unit, data unit and sensor ID/name.

Data which need to be transferred from the sensor to the data hub using wired digital signal is:

- Sensor ID/NAME
- Sampling rate used
- Start date (for example: 14.10.2014)
- Start time (for example: 11:58:31.600)
- Time unit (seconds)
- Measurement unit (g, uStrain, mm/s..)
- Measured data

The protocol is to be defined bilaterally further into the development. To support self-test functionality, the sensor system must be able to accept an incoming request for a self-test, and be able transmit the result back to the data hub.

3.2.4. Acceleration sensors interface description

The accelerometers will be connected to the data hub by wire. The accelerometer provides one cable with 12 wires. Through this cable power, signals and test input is transferred. The electrical specifications of the accelerometer interface are listed in Table 12.

Parameter	Specification
Power supply	+10 to +15VDC
Power consumption	~ 40mA@12V, ~0.5W
Signal	± 10 Volt differential output
Self-test	+10V for 1 second

Table 12-Accelerometer communication module interface

Pin assignment
Table 13 lists the expected pin assignment from the sensor.

Pin	Signal	Comment	Color	
1	OUTPUT X (+)	0 V ± 5 V voltage output, 47 Ω output impedance	White	
2	OUTPUT X (-)	0 V ± 5 V voltage output inverted, 47 Ω output impedance	Brown	
3	OUTPUT Y (+)	0 V ± 5 V voltage output, 47 Ω output impedance	Green	
4	OUTPUT Y (-)	0 V ± 5 V voltage output inverted, 47 Ω output impedance	Yellow	
5	OUTPUT Z (+)	0 V ± 5 V voltage output, 47 Ω output impedance	Grey	
6	OUTPUT Z (-)	0 V ± 5 V voltage output inverted, 47 Ω output impedance	Pink	
7	TEST INPUT	Test input, output will result in a sensor step response	Blue	
8	GROUND	Ground, not connected to mechanical ground	Red	
9	+12 VDC power	Power input, +10 to +15 VDC range, 40 mA @ +12 VDC	Black	
10	GROUND	Ground, not connected to mechanical ground	Violet	
11	AUX	Auxiliary input (reserved)	-	
12	GROUND	Ground, not connected to mechanical ground	-	

Table 13-Accelerometer connector pin assignment.

Power
The accelerometer requires to be provided with +12VDC by a host but between +10 and +15VDC is tolerated. The consumption is approximately 0.5W, but up to 1W should be supported.

Signals
The transmitted signal will be an Analogue differential 10V signal, where the voltage is proportional to the acceleration. Due to the differential signal, each axis of measurement requires two wires. To support of to three axes per sensor, 6 wires are assigned for signal transfer.

Self-test
The sensor supports self-test which is enabled when the signal on the self-test input wire is pulled high to +10VDC. The duration of time the self-test input is high is equal to the duration of the test feedback from the sensor.

3.2.5. Temperature sensors interface description

Interface 1: Analogue interface described previously (±10V differential)
Interface 2: wired digital signal interface described previously with the corresponding protocol.

3.2.6. Data Hubs – Wireless Sensor Nodes Interface

The wireless sensor nodes will be the communication means that convey measurements retrieved from the strain sensors towards the data hubs. The technology to be used will be most probably 802-15.4-ZigBee (Pro) and there will be considered the following topologies, tree and mesh. According to the IEEE 802.15.4 specifications devices in a ZigBee Pro network can be either FFDs or RFDs. A full function device is capable of performing all the duties described in the IEE 802.15.4 standard and can accept any role in the network. On the other hand, a reduced function device has limited capabilities.
According to the IEEE 802.15.4 specifications [6,7] there are three supported frequency bands:

- 868 - 868.6 MHZ (868 MHz band)
- 902 - 968 MHz (915 MHz band)
- 2400 - 2483.5 MHz (2.4 GHz band)

Especially for the latter band IEEE 802.15.4 adopts many mechanisms to enable it to coexist with other radio products (such as Wi-Fi modules that are also implemented within the RECONASS communication module framework):

- DSSS (Direct Sequence Spread Spectrum): The spreading technique employed by IEEE 802.15.4, makes use of a pseudo-random code sequence, often called a “chipping sequence”, which is transmitted at a maximum rate called the chip rate. The chipping sequence is used to directly modulate the basic carrier signal- hence the name “direct sequence” – and to encode the data being transmitted. DSSS technique extends band of frequencies, which can reduce the occupancy of an interference source and get better coexistence with other interference sources.
- CCA (Clear Channel Assessment): The clear channel assessment (CCA) is performed according to at least one of the following three methods:
  - Energy above threshold, CCA reports a busy medium upon detecting any energy above the Energy Detect Threshold.
  - Carrier sense only, CCA reports a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. This signal may be above or below the ED threshold.
  - Carrier sense with energy above threshold, CCA reports a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4 with energy above the ED threshold.
- Dynamic Channel Selection: ZigBee allows dynamic channel selection, a scan function steps through a list of supported channels in search of beacon, receiver energy detection, link quality indication (Frequency agility feature).

- Acknowledgment transmission and retries: If a receiving device fails to receive or handle the received data frame for any reason, the message will not be acknowledged. If the sender does not receive an acknowledgment, it assumes that the transmission was not done successfully and retries the data frame transmission.

Concerning the coexistence of ZigBee Pro and Wi-Fi devices operating in adjacent frequency bands this will not be an issue in terms of interference. The IEEE 802.11 Wireless LAN (WLAN) standard adopts DSSS and operates in a total of 14 channels available in the 2.4GHz band, numbered 1 to 14, each channel with a bandwidth of 22MHz and a separation of 5MHz. The IEEE 802.15.4 is also based on DSSS. A total of 16 channels are available in the 2.4GHz band, numbered 11 to 26, each with a bandwidth of 2MHz and a channel separation of 5MHz. 802.15.4 channels 15, 20, 25, 26 are not overlapped with Wi-Fi channels. PER (Packet error rate) has close relationship with distance (between interference source and receiver) and differences of centre frequencies (between interference source and receiver). They can even coexist within very short range (2 meters) even when difference of centre frequencies is considerable, however, when their centre frequencies are very close, they can coexist only out of long distance (even several meters). It shows that, if the interference source is more far from receiver, they can coexist better. The interference with Wi-Fi, caused by ZigBee, is smaller than the interference with ZigBee, caused by Wi-Fi and this is because ZigBee bandwidth (2MHz) is much smaller than Wi-Fi bandwidth (22MHz), so ZigBee is a kind of narrowband interference source to Wi-Fi.

ZigBee network layer contains three kinds of logical devices:

- ZigBee Coordinator (ZC): The ZigBee coordinator is responsible for initialling, maintaining and controlling the network. If the ZigBee coordinator is also the principal controller of a personal area network is called PAN coordinator. The ZigBee coordinator is always a FFD.
- ZigBee Router (ZR): The ZigBee router forms the backbone of the network. The ZigBee router is always a FFD.
- ZigBee End Device (ZED): End device from an end-user perspective can be a sensor for example. ZigBee end device can be either a FFD or RFD. In case of RFD, ZigBee end device can't act as coordinator or router.

The basic layers of the ZigBee protocol stack are described below, from top to bottom:

- Application layer: The Application layer contains the applications that run on the network node. These give the device its functionality - essentially an application converts input into digital data, and/or converts digital data into output.
- Network layer: The Network layer provides the ZigBee PRO functionality and the application interface to the IEEE 802.15.4 layers (Data and physical). The layer is concerned with network structure and multi-hop routing.
- Data link layer: The Data Link layer is provided by the IEEE 802.15.4 standard and is responsible for addressing - for outgoing data it determines where the data is going, and for incoming data it determines where the data has come from. It is also responsible for assembling data packets or frames to be transmitted and disassembling received frames. In the IEEE 802.15.4 standard, the Data Link layer is referred to as IEEE 802.15.4 MAC (Media Access Control) and the frames used are MAC frames.
- Physical layer: The Physical layer is provided by the IEEE 802.15.4 standard and is concerned with the interface to the physical transmission medium (radio, in this case), exchanging data bits with this medium, as well as exchanging data bits with the layer above (the Data Link layer). In the IEEE 802.15.4 standard, the Physical layer is referred to as IEEE 802.15.4 PHY.

In addition, according to the ZigBee specification there are two models of routing:

- **Mesh routing**: Permits path formation from any source device to any destination device via a path formed by routing packets through neighbours. Table routing employs a simplified version of Ad Hoc on Demand Distance Vector Routing (AODV). Many to one and source routing features address limitations in mesh routing. Many to one allow any device in the network to route data to a well-known concentrator through a single route table entry in every device. This way many multiply concentrators are possible. Source routing allows a concentrator to route responses back to each device supplying a many to one data request without additional route table entries.

- **Tree cluster routing**: It can directly infer the routing paths from network addresses based on the parent-child relationships. No extra memory and broadcast overhead are required. However, it often provides fragile routing paths since it is prone to the single point of failure problem. If one of parent child links in the routing path is broken, it cannot recover the routing path by itself. Moreover, routing paths could be longer because the data packets follow the hierarchical tree topology to the destination even if the destination is close to.

ZigBee Pro in a mesh or hybrid topology (mesh - tree) will use the mesh routing protocol. The greatest advantages of ZigBee Pro lie on the self-healing and discovery characteristics. Unexpected interruptions of the network can be addressed by redirecting the communication paths dynamically. The ZigBee Pro network is initialized by sending discovery messages between nodes. For the needs of RECONASS we propose the use of the hybrid topology.

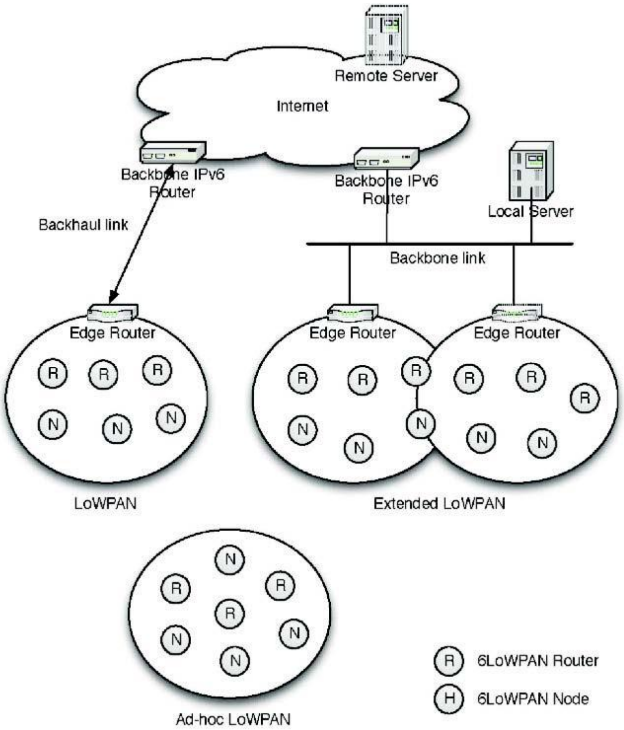


Figure 28-Model of 6LoWPAN architecture

Another option being currently considered as a solution that provides value with respect to power consumption and performance/deployment features for the network of wireless modules is 6LoWPAN [3]. The nodes in 6LoWPAN networks are 6LoWPAN Hosts, 6LoWPAN Routers and Edge Routers. Hosts send and receive packets but do not route; 6LoWPAN routers perform IP routing within the LoWPAN, and Edge Routers route between 6LoWPANs and other IP networks. A 6LoWPAN IPv6 subnet includes all the nodes which share the same IPv6 prefix covering a whole LoWPAN or Extended LoWPAN. A LoWPAN is defined by the nodes sharing the same IPv6 prefix, usually with a single Edge Router as shown in Figure 28. A LoWPAN may be connected to other IP networks over a backhaul link, e.g. xDSL or GPRS.

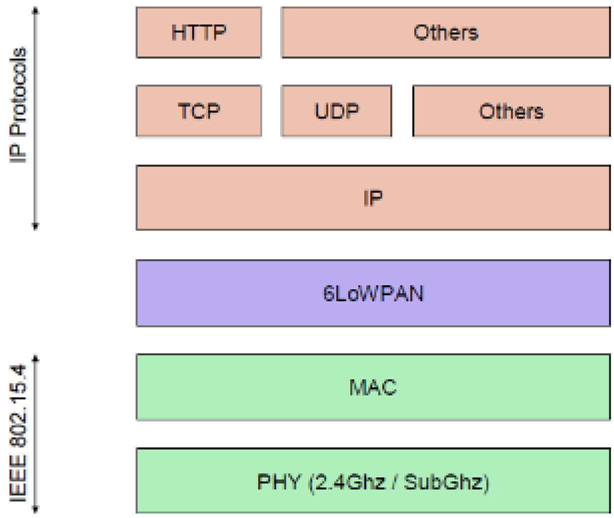


Figure 29-6LoWPAN protocols stack

The basic layers of the 6LoWPAN protocol stack shown in Figure 29 are described below, from top to bottom:

- **Application layer:** Uses a socket interface for a specific application. Each 6LoWPAN application opens a socket which is then used to receive or send packets. Each socket is associated with a protocol, TCP or UDP, and source and/or destination ports.
- **Transport layer:** It delivers data segment to the appropriate application process. In this layer, there are two types of transport protocols; User Datagram Protocol (UDP) and Transmission Control Protocol (TCP).
- **Network layer:** Provides the internetworking capability to nodes. The main considerations of this layer are addressing, mapping and routing protocols. Route over routing decision occurs in this layer.
- **Adaption layer:** The 6LoWPAN format delineate on IPv6 communication is carried in 802.15.4 frames and specifies the adaptation layer's key elements. 6LoWPAN has three primary elements (Fragmentation and reassembly, header compression and routing). Mesh under routing decision occurs in this layer.
- **Data link layer:** This layer which is the MAC sub-layer, provides two services: the MAC data service and the MAC management service interfacing to the MAC sub-layer management entity (MLME) service access point (SAP)(MLMESAP).
- **Physical layer:** This layer provides two services: the PHY data service and the PHY management service interfacing to the physical layer management entity (PLME) service access point (SAP) known as the PLME-SAP.

Routing in 6loWPAN can be divided in two categories and depends on the decision which layer is used:

- **Mesh under (Link layer):** To send a packet to a particular destination, the EUI 64 bit address or the 16 bit address is used and sent to the neighbour node so that it can reach to the destination. An IP packet sent by the network layer is fragmented by the link layer into number of fragments. These fragments travel independently and reach the destination and at the destination the link layer reassemble them into the IP packet and give it to the network layer. In case if any fragment is lost, all the fragments should again be retransmitted to the destination.
- **Route over (Network layer):** The IP routing supports the forwarding of packets with the help of IP routing tables and IPV6 hop-by-hop options. IP packet is fragmented at the link layer into a number of packets and sent to the next hop. At the next hop all these fragments are reassembled by the link layer and sent to the network layer. At the network layer it checks whether the packet is

to it or not, if not it will transmit to the next hop according to the routing table. If one or more fragments is missing or lost then all the fragments has to be retransmitted at one hop distance.

The routing function within the IP/6LoWPAN network resides above the IP layer, making each sensor network node both an IP router and an end point. By routing above IP, each 802.15.4 hop becomes an explicit IP hop, creating IP level visibility into the network topology. The standard routing protocol uses a Rendezvous Point (RP), typically the 6LoWPAN router. Based on a distance vector protocol, the routing protocol is responsible for picking a default route to the RP. To guard against variations in wireless connectivity, two successor default routes are maintained and used whenever the primary route fails. Thus each node forms a triple-redundant path for reliable communication with the RP. In choosing routes, nodes choose next hops that minimize the cost to the RP. To compute the cost metric, link statistics are gathered from explicit beaconing while the network is forming, and inferred from data traffic in the steady state. This 'adaptive beaconing' approach keeps the network robust in volatile environments while minimizing control overhead in stable conditions. Once a path is established, nodes inform the RP of their location, allowing the RP to route packets back to individual sensor nodes.

The ability of the 6LoWPAN wireless modules to act as end devices and routers at the same time is a major advantage. This permits us designing the network topology without adding intermediate routers between data hubs and wireless nodes. In addition, many paths will be available for choosing the best route every time. Some protocols for routing are described as below. The 6LoWPAN Ad-Hoc On-Demand Distance Vector Routing protocol (LOAD) is a simplified routing protocol based on Ad hoc On-Demand Distance Vector (AODV) for 6LoWPAN. This routing protocol is a single path routing protocol. It enables multi-hop routing between IEEE 802.15.4 devices to establish and maintain routing routes in
6LoWPAN.
Besides that, Dynamic MANET On-demand for 6LoWPAN Routing (DYMO-low) is another 6LoWPAN routing protocol that based on Dynamic MANET On-demand (DYMO). DYMO-low positioning is underneath of IP layering in creating a mesh network topology of IEEE 802.15.4 devices. It use single wireless interface underneath and unbeknownst to IP. The significant feature in DYMO-low is it can support either 16-bit link layer short address or IEEE 64-bit extended address (EUI-64). On the other hand, considering low power, low memory, low bandwidth and small packet size of the 6LoWPAN devices, the on-demand multi-hop routing with routing table and EUI-64 identifier may limit the scalability. Hierarchical Routing for 6LoWPAN (HiLow) is employed in 6LoWPAN because of the capability of the dynamic assignment of 16-bit short addresses [6]. Extensively, it reduces the overhead of maintaining routing tables and support larger scalability. Different routing protocols of 6LoWPAN are compared in Table 14.

Parameter	AODV (WSN)	LOAD	DYMO-low	HiLow
RERR MESSAGE	USE	USE	USE	NO USE
SEQUENCE NUMBER	USE	NO USE	USE	NO USE
PRECURSOR LIST	USE	NO USE	NO USE	NO USE
HOP COUNT	USE	OPTIONAL	OPTIONAL	USE
HELLO MESSAGE	USE	NO USE	USE	NO USE
LOCAL REPAIR	USE	USE	NO USE	USE
ENERGY USAGE	HIGH	LOW	LOW	LOW
MEMORY USAGE	HIGH	MEDIUM	MEDIUM	LOW
MOBILITY	MOBILE	MOBILE	MOBILE	STATIC
SCALABILITY	LOW	LOW	LOW	HIGH
ROUTING DELAY	HIGH	LOW	HIGH	LOW
CONVERGENCE TO TOPOLOGY CHANGE	FAST	FAST	FAST	SLOW

Table 14-6LoWPAN routing protocols comparison

With respect to the specifications for the wireless sensors network, the LOAD routing protocol complies. Also as it has been previously described, LOAD protocol is an improved version of AODV.

6LoWPAN offers interoperability with other wireless 802.15.4 devices as well as with devices on any other IP network link (e.g., Ethernet or Wi-Fi) with a simple bridge device. Bridging between ZigBee and non-ZigBee networks requires a more complex application layer gateway. The key requirement for IPv6 over 802.15.4 is that the maximum transmit unit (MTU) must be at least 1280 byte packets (per RFC 2460). Since the IEEE 802.15.4 standard packet size is 127 octets, an adaptation layer must be implemented to allow the transmission of IPv6 datagrams over .4 networks.

IP routing over 6LoWPAN links does not necessarily require additional header information at the 6LoWPAN layer. This cuts down on packet overhead and allows more room for the payload data. Also, the typical code size for a full-featured stack is 90KB for ZigBee and only 30KB for 6LoWPAN. Further to this, 6loWPAN provides built-in AES128 encryption, which is part of the IEEE 802.15.4 standard. All the major players in the semiconductor industry, such as Texas Instruments, Freescale and Atmel, promote and supply 802.15.4 chips which can be used for either ZigBee or 6LoWPAN. There is at least one open source stack available, and companies such as Archrock and Sensinode license their 6LoWPAN stacks.

3.2.7. Wireless Sensor Nodes – Strain sensors Interface

The wireless radio module will be supported by a microcontroller that features an on board ADC that is connected to the analogue strain sensor.As extracted from chapter 2.1.1, the microcontroller will be provided within the module of the sensor node. Concerning the sensors nodes a proposal includes the Waspmotes from Libelium [14]. Below we will provide a typical architecture for connecting the proposed strain model with a Waspmote. Waspmote hardware architecture has been specially designed to be extremely low consumption. Digital switches allow turning on and off any of the sensor interfaces as well as the radio modules. Two different sleep modes make Waspmote the lowest consumption sensor platform in the market (0.7uA).

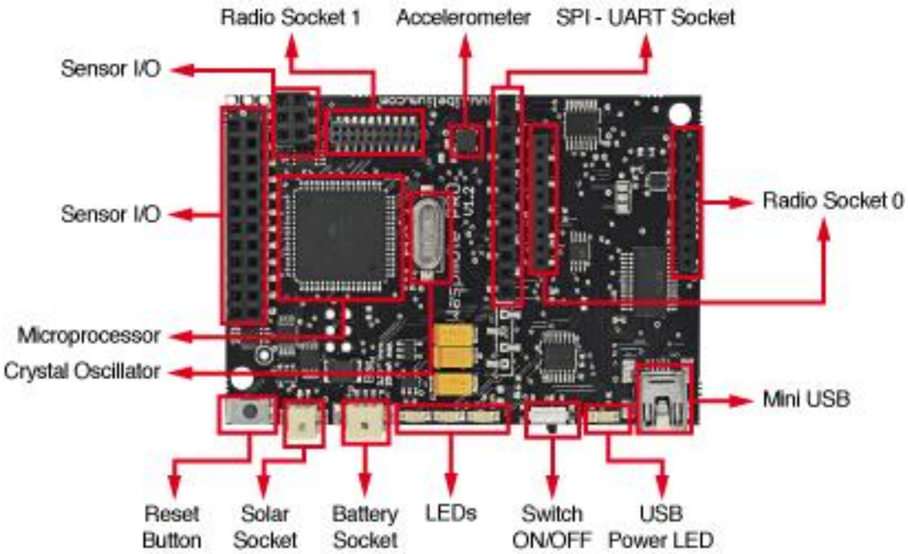


Figure 30-Waspmote board top view

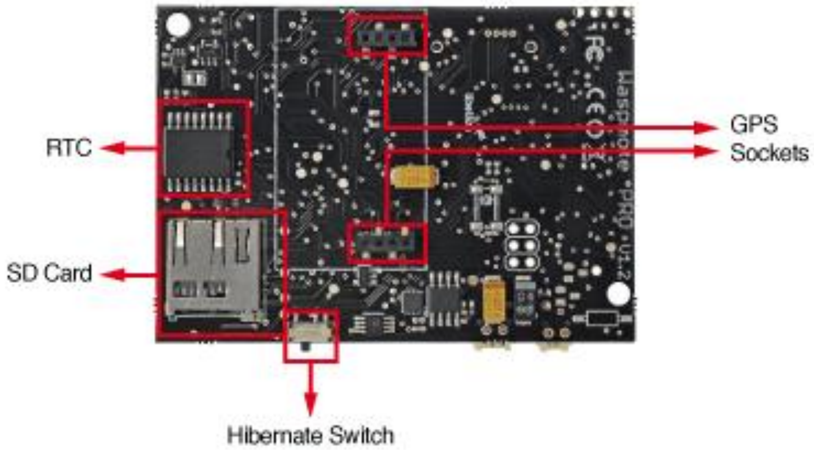


Figure 31-Waspmote bottom board view

From Figure 30 and Figure 31 one can see that Waspmote is a board with many capabilities. It supports various types of inputs/outputs, various modes of sleep modes, sockets for various types of sensor and radio modules. **Error! Reference source not found.** contains the main characteristics of a Waspmote board.

Parameter	Value
Microcontroller	ATmega1281
Frequency	14MHz
SRAM	8KB
EEPROM	4KB
FLASH	128KB
SD CARD	2GB
WEIGHT	8KB
DIMENSIONS	4KB
TEMPERATURE RANGE	-10℃ +65℃
CLOCK	RTC (32KHz)

Table 15-Waspmote board characteristics

Concerning the power consumption, **Error! Reference source not found.** summarizes the various modes urrently supported.

Mode	Consumption
ON	15mA
SLEEP	55uA
DEEP SLEEP	55uA
HIBERNATE	0.7uA

Table 16-Waspmote board consumption modes

In subsection 3.2.6 it has been described that the primary choice for radio technology is ZigBee Pro and preliminary considerations exist for implementing 6lowPAN. Waspmote board supports both of them as it can be seen in Figure 32:

Figure 32-802.15.4/ZigBee Pro module

The different models of of XBee are compared in Table 17.

Model	Protocol	Frequency	Tx power	Sensitivity	Range*
XBee-802.15.4-Pro	802.15.4	2.4GHz	100mW	-100dBm	7000m
XBee-ZB-Pro	Zigbee-Pro	2.4GHz	50mW	-102dBm	7000m
XBee-868	RF	868MHz	315mW	-112dBm	12Km
XBee-900	RF	900MHz	50mW	-100dBm	10Km

Table 17-Comparison of XBee models

* Line of sight and 5dBi dipole antenna.

Figure 33-6lowPAN module

The specifications of different parameters of the 6lowPAN radio module at two frequencies of operation are listed in Table 18 and in Table 19 and it is shown in Figure 33.

Parameter	Value
CHIPSET	AT86RF231
FREQUENCY	2.4GHz
LINK PROTOCOL	IEEE 802.15.4
USAGE	WORLDWIDE
SENSITIVY	-101dBm
SECURITY	WEP, WPA, WPA2
OUTPUT POWER	3dBm
ENCRYPTION	AES 128B

Table 18-6lowPAN radio module (2.4GHz)

Parameter	Value
CHIPSET	AT86RF212
FREQUENCY	868MHz
LINK PROTOCOL	IEEE 802.15.4
USAGE	EUROPE
SENSITIVY	-110dBm
SECURITY	WEP, WPA, WPA2
OUTPUT POWER	10dBm
ENCRYPTION	AES 128B

Table 19-6lowPAN radio module (868MHz)

Any of the two radio modules fit perfect on the Waspmote board. Their component pins must be aligned properly to the radio socket 0 interfaces on the board. This interface is located at the top view of the board. For connecting sensors on the Waspmote there are two ways. One is to use "basic" sensor modules from the Libelium itself. On the other hand, we can use sensors that their data outputs comply with the following industrial protocols: RS-485, RS-232, CAN-Bus, Modbus and 4mA-20mA loop.

Considering the proposed hardware in section 2.1 for the strain gauge sensors model, we will use the industrial protocol of 4mA-20mA loop. To achieve this, we will use the 4mA-20mA sensor board, by Libelium as shown in Figure 34.

Figure 34-4mA/20mA current loop module

Depending on the source of current for the loop, devices may be classified as active (supplying power) or passive (relying on loop power). From the proposal of strain sensors in chapter 2.1.1 we can derive that the strain model will be classified as active and will have three termination wires (Type 3 transmitter). Type 3 transmitters have 3 wires powered by the source voltage in them. In this case the transmitter is the power source for the current loop. The transmitter common is connected to the common of the receptor.

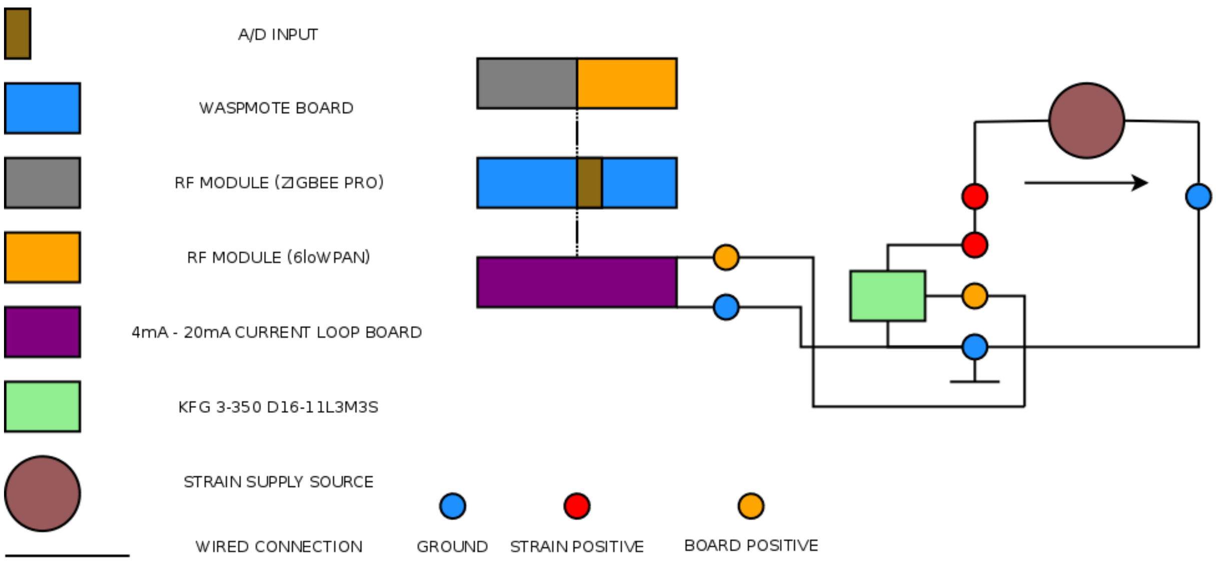


Figure 35-Connection diagram for strain sensor and 4mA-20mA current loop

Figure 35 presents the necessary wiring topology for connecting the proposed model of strain with one 4mA-20mA current loop board. The operation of this circuit is straightforward: the output voltage from the strain module will be converted to a proportional current, with 4mA normally representing the zero-level output, and 20mA represents the full scale output. Then, the 4-20mA current will be converted back into a voltage which in turn will be applied at the A/D input of the Waspmote board. The A/D will convert the analogue voltage to digital value. Afterwards, this digital value will be inserted as payload information to the communication datagrams of ZigBee Pro or 6loWPAN radio modules for transmission.
We will be able to program the microcontrollers on the Waspmote boards. There is the Waspmote Pro IDE which is a software development kit. It will be used for writing and uploading code to Waspmote. It also will be able to monitor the serial output and be used in debugging. The programming of the Waspmote microcontrollers will rely on Waspmote PRO API v011 or newer. The Waspmote API contains all libraries that are needed to compile programs. The microcontroller of the Waspmote will be responsible to appropriately format the data information from the strain gauge sensors towards the data hubs (see section 3.2.) After formatting, data will be included as the payload over ZigBee Pro or 6loWPAN network.

CONCLUSIONS

This report on the LPS and sensor node system architecture presents the work in progress within WP2 towards the design, development and implementation of the RECONASS monitoring and accurate positioning system with a communication framework that permits unsusceptible, secure and resilient data exchange inside the structure of interest.

To the above scope, this deliverable gave a detailed outline of the proposed architecture for the RECONASS system and components as well as interfaces of the LPS, strain sensors, accelerometers and temperature sensors to the data hubs.

Regarding the LPS system architecture, we are confident that our designs and selection of the LPS tags, coordinators and their interfaces supported with carrier-phase based GPS receivers will meet the user requirements and allow for a successful implementation of the whole system. In addition the design process is closely considering performance improvements (i.e. accuracy and precision) as well as solutions that decrease power consumption, costs and tag size in comparison with the current state of the art developments. Apart from the above, an additional challenge to be considered in the LPS implementations deals with proper placing of the GPS receiver modules so they have a clear view of the sky to give the needed centimetre accuracy so as to tackle issues arising from the overall movement of the structure when a disaster occurs.

Concerning the strain, acceleration and temperature sensors the proposed solutions comply with the requirements posed by the structural engineer experts within the project that require a rich set of values to carry out the overall structural assessments. At the same time the proposed sensors address the requirements expressed by the end-users providing in parallel performance features that permit additional customisations to fit the measurement purposes a harsh disastrous environment.

Although this deliverable mainly reported on the LPS and sensor node architecture, the communication module represents an integral part of the overall system design since it enables the various bidirectional interfaces and routes to be utilised for the necessary and critical data exchange. In this scope, the interfaces of the communication module utilised in the Local Area Network (LAN) and the Local Sensor Network (LSN) of the RECONASS overall communication architecture were further refined and presented based on the initial design performed in D1.4. From a communication point of view, we focused on the hardware (technologies and modules) and the network considerations towards the final development and integration of the whole RECONASS communications system. Upon successful development and implementation of the identified LAN/LSN interfaces and networking, it is expected that the communication module will be fully compliant with the user requirements and additionally it will preserve a high degree of robustness, resilience and reliability to serve continuously as a communication link between the various entities (i.e. sensors, nodes and data hubs).

REFERENCES

[1] http://www.novatel.com/an-introduction-to-gnss/chapter-4-advanced-gnss-concepts/real-time-kinematic-rtk/
[2] http://docs.swiftnav.com/pdfs/piksi_datasheet_v2.3.1.pdf
[3] https://tools.ietf.org/wg/6lowpan/
[4] Rife, J., Khanafseh, S., Pullen, S., De Lorenzo, D., Kim, U. S., Koenig, M., Pervan, B. “Navigation, interference suppression, and fault monitoring in the sea-based joint precision approach and landing system”. *Proceedings of the IEEE*, 2008, 96(12), pp. 1958-1975.
[5] Hedgecock, W., Maroti, M., Sallai, J., Volgyesi, P., & Ledeczi, A. “High-accuracy differential tracking of low-cost GPS receivers”, in *Proceeding of the 11th annual international conference on Mobile systems, applications, and services*, June 2013, pp. 221-234
[6] http://standards.ieee.org/about/get/802/802.15.html
[7] http://www.zigbee.org/
[8] http://www.u-blox.de/images/downloads/Product_Docs/LEA-6_DataSheet_(GPS.G6-HW-09004).pdf
[9] Electronic Communications Committee, ERC Recommendation 70-03, Available: http://www.erodocdb.dk/Docs/doc98/official/pdf/Rec7003e.PDF
[10] Federal Communications Commission, Part 18, Available: http://www.gpo.gov/fdsys/pkg/CFR-2010-title47-vol1/pdf/CFR-2010-title47-vol1-part18.pdf
[11] Trenz Electronic TE0600 Series, Available: http://www.trenz-electronic.de/de/produkte/fpga-boards/trenz-electronic/te0600.html
[12] N. Joram, B. Al-Qudsi, J. Wagner, A. Strobel, and F. Ellinger, “Design of a multi-band FMCW radar module,” in *10th Workshop on Positioning Navigation and Communication (WPNC)*, 2013, pp. 1–6.
[13] Sandra Sendra, Miguel Garcia, Carlos Turro, Jaime Lloret, “WLAN IEEE 802.11a/b/g/n Indoor Coverage and Interference Performance Study”, in *International Journal on Advances in Networks and Services*, vol 4 no 1 & 2, 2011, Available: http://www.iariajournals.org/networks_and_services/
[14] http://www.libelium.com/products/waspmote/overview/
[15] E. D. Kaplan and C. J. Hegarty, eds. Understanding GPS: principles and applications. Artech house, 2005.