Grant Agreement no. 287613

HYDROBIONETS

Autonomous Control of Large-scale Water Treatment Plants based on Self-Organized Wireless BioMEM Sensor and Actuator Networks

INSTRUMENT: Collaborative Project (Small or Medium Scale Focused Research Project)

OBJECTIVE: ICT-2011.3.3

D2.5: Recommended system specifications

Due Date of Deliverable: 31st March 2014
Completion Date of Deliverable: 3rd October 2014
Start date of project: 1st October 2011 Duration: 36 months

Lead partner for deliverable: Acciona Agua

Revision: v1.0

Project co-funded by the European Commission within the 7th Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

Document History

Issue Date	Version	Changes Made / Reason for this Issue
14th July 2014	v0.1	First draft
29th August 2014	v0.2	Revision after partners updates
5th September	v0.3	Partners updates
16th September	v0.4	Partners updates
22th September	v0.5	Partners updates
24th September	v0.6	Minor corrections
3rd October	v1.0	Final version

Document Main Author(s): **Clara Sanroma (Acciona)**

Document signed off by: **David Wenn (iXscient)**

Copyright

Table of Contents

1. Introduction

The HYDROBIONETS project applies a scenario-driven development methodology to address the currently unmet need for a heterogeneous Wireless BioMEM Sensor and Actuator Network (WBN) applied to autonomous control of large-scale water desalination and treatment plants. WP2 considers the overall system aspects of the WBN solution that is proposed in this project, defining also the concrete application scenarios of interest. These scenarios are the basis for the technical studies and determine many system requirements such as type and spatio-temporal density of measurement data, spatial extension to be monitored, geographical layout of the WBN, actuators (i.e. for controlling bacteria activity), necessary co-operative tasks and the overall communication architecture of the system.

Deliverable D2.5 describes the recommended system specifications for a potential full-scale WBN system based on the results from the technical studies and pilot plant installation. The information provided is based on parameters that describe the system as a whole in terms of operation, more detailed description of each part of the system is done in the correspondent deliverables. This deliverable describes the specifications of the three main parts of the HYDROBIONETS system:

- Sensors specifications
- Network and control specifications
- Data management and visualization

It also contains recommendations for HYDROBIONETS system improvements and an operating manual.

Note that this deliverable contains an appendix which includes confidential information. Therefore, the deliverable is provided in two different versions – a confidential version for the European Commission and a non-confidential version, with the appendix removed, for wide public dissemination.

2. System requirements and recommended specifications tables

The following tables describe the parameters that were set as requirements at the beginning of the project and how these requirements have been addressed in the specifications:

Table 1: System requirements and specifications of HYDROBIONETS sensor platform.

Requirements	**Specifications**			
Item	**Proposed value**	**Referred WP and/or Deliverable/s**	**Final value**	**Description**
Minimum sensor lifetime	12 months	WP3	12 months	No degradation of the sensor has been observed in 4 months. It is expected that the sensor can work properly for 12 months.
Degree of protection against water and dust (IP code)	Typically IP 55; if possible up to IP 67	WP8 and WP9 (standardization)	IP65	Both the external and the internal enclosures
Physical requirements: parts in contact with water (resistance to corrosion, mechanical resistance, etc.)	pH: 2 to 10 Temperature: 5 to 45ºC Pressure: up to 5 bar	WP3 and WP8	pH: not tested Temperature: 5 to 45 ºC Pressure: up to 2 bar	Improper valve operation and sensor cell leakage might occur at higher pressure
Physical requirements: other parts (resistance to corrosion, mechanical resistance, etc.)	Able to withstand saline environments	WP8	Withstands saline environment	Only external signs of saline environment have been observed yet
Calibration frequency	1 per month maximum (included within the maintenance dedication time)	WP3	No external calibration required	Internal calibration of the sensor electronics is carried out prior to all measurements in order to minimize temperature dependence
Sensor module (WBN) dimensions	30 cm x 20 cm x 10 cm	WP8	30 cm x 20 cm x 10 cm	

Battery lifetime	12 months (2 months as an intermediate development)	WP3, WP4 (D4.2), WP5, WP6 and WP8	2 months without duty-cycling, at least 12 month with duty cycling	Due to the in-network processing and iterative control, communication is a major source of power consumption. Energy optimization and balancing is applied to decrease the energy consumption, and minimize the maximum energy consumption of the nodes.
Annual Maintenance dedication (all sensor modules)	5 days/year (40 hours)	WP3 and WP8	3 days/year	
KCl bottle duration	> 2 months	WP3 and WP8	2 months	Based on the current measurement periodicity and protocol 1 litre of KCl lasts 2 months
Installation dedication	Less than 30 minutes per sensor module.	WP8	Less than 30 minutes per sensor module.	
Installation connections	Standard hydraulic/pneumatic tubing connections	WP8	Standard hydraulic/pneumatic tubing connections	Both internal and external tubing

Table 2: System requirements and specifications of overall HYDROBIONETS system.

Requirements			Specifications	
Requirement	**Value**	**Affected WP and/or Deliverable/s**	**Final value**	**Description**
System capacity (number of sensors in the system network)	From 8 to 200	WP4 (D4.1 and D4.2) and WP5	The proposed solution is scalable in the number of sensors.	Number of sensors includes the sensors developed in the project, and sensors that are expected to be connected with wireless links during the lifetime of the network. To support the required number of sensors, a multi-tier architecture with decreased tier 1 traffic and optimized tier 1 MAC and routing protocols have been designed.
Connection/ communication with the water treatment plant control systems	Bi-directional communication with the plant PLC system by an OPC	WP7	Bi-directional via OPC client for Java	A specific module, which uses a Java based OPC client (from Utgard, probably). This module is part of the Gateway architecture and implements the bi-directional communication with the OPC server of the plant.
Lifetime of the whole system	10 years	WP3 and WP4 (D4.2)	Minimum of 10 years	Wireless reprogramming is proposed to allow long network lifetime, despite the more limited lifetime of the sensor nodes and the technology advances.
Bottleneck lifetime	12 months (2 months as intermediate development)	WP3	6 days	WSN battery lifetime is the bottleneck. The value of 6 days assumes the use of a standard pair of alkaline batteries (at 2500-3000 mAh).
Data rates	In the order of kb/s, see D4.2.	WP4 (D4.2), WP5 and WP6	Order of kb/s	Optimization of MAC and routing to allow the high data rates in periods on intensive traffic during distributed data processing and in-network control.
Security against cyber attacks	No undesired access to current system. No undesired plant shut-down.	WP7	Only authorized access is guaranteed. The passwords of validated users are	Security is controlled via the visualization platform

	(This issue is not part of the project)		stored and protected in a database using Bcrypt hashing	
Electromagnetic compatibility	According to European directive; to be confirmed at the pilot plant	WP3 and WP8		EMI compatible by design, not measured by standard
Faults (over the final signal sent to the current control)	< 0.5%	WP6 and WP7	-	The control module has not been integrated yet in the HYDROBIONETS platform so as to perform explicit computation of fault rates
Fault management	System never produces a production shutdown Reliability > 99.99966%	WP6 and WP7	System never produces a production shutdown	Current implementation of the HYDROBIONETS platform only provides notifications for distinct extreme events. Automatic production shutdown is not supported yet
Annual Maintenance dedication (excluding WBN)	1 day per year	WP2 and WP9	One day per year plus additional on demand operations if needed.	The addition, removal or reallocation of any node, as well as important and permanent changes in the channel conditions (due to new electrical equipment installation) would require some medium access control reconfiguration.
Area to be covered	300 m x 300 m	WP4 (D4.1 and D4.2)	The proposed solution is scalable in the size of the area to be covered.	The initial measurements at the pilot plant motivate the need of a dense sensor network, with relatively low single hop distances (below 10m). This in turn motivates the introduction of the multi-tier architecture, to achieve the required coverage, keeping the communication costs and delays acceptable.
Installation dedication (new system dedication time)	5 days	WP2 (business case) and WP9 (exploitation)	-	The installation tasks should include the medium access control protocol 3calibration and fine tuning. This includes measuring inter-node distances, thresholds calculation, nodes reprogramming and performance tests.

3. Overall components description

Table 3 describes the list of HYDROBIONETS system components and a description of their functionality.

Table 3: List of components of HYDROBIONETS system.

Component	**Description**
Sensor platform	
Sensor cell	The sensor cell allows the seawater to be flowed over the chip containing the sensors so that the bacteria can grow on the sensor surface. It also allows KCl solution to be flowed over the sensor during the measurement period while ensuring that there no leakages which could affect the measurements. The sensor chip has the connections out of the fluidic chamber of the cell and with its USB connector supplies the data from the sensors to the readout electronics in the mote.
Electronics	The sensor module incorporates two PCBs excluding the XM1000 WSN node. The main parts and roles of the electronics are: analogue front-end (interfacing to the sensing element and providing the excitation signal as well as conditioning the received signal), impedance spectroscopy, fluidic control and power management. For the measurement control a dedicated microcontroller is integrated. This MCU communicates with the XM1000 node.
Batteries	Sensor electronics: 1pc. 12V, 1200mAh, rechargeable WSN mote: 2pcs. 1.2V, 1900mAh, rechargeable
Fluidics (valves, tubing, connectors)	Two bi-static valves (Steiger, PI-200): 20ms of +/-12Vdc pulses are required for its actuation. Conventional pneumatic 6/4mm tubing and connectors (8pcs per sensor module)
Motes (wireless communication module)	End-to-end connectivity with the µserver for transferring biofilm and network management data to the upper tiers of the HYDROBIONETS platform. Interaction with the remaining components of tier 1 (WBN nodes, relay nodes) and tier 2 (µserver).
Relay nodes	
Motes (wireless communication module)	Support the end-to-end connectivity between the WBN nodes and the µserver. Interaction with the remaining components of tier 1 and tier 2 for establishing reliable communication paths between source and destination nodes.

Microserver	
Sensing and actuating control unit	Responsible for gathering and pre-processing the biofilm data received by the WBN nodes. Interacts with the Application Service Handler, for forwarding the processed information to the Gateway.
WBN-Cluster MGM unit	Responsible for gathering and pre-processing the network management data received by the WBN nodes. Interacts with the Application Service Handler, for forwarding the processed information to the Gateway.
WBN-Cluster storage unit	Not implemented
Application Service Handler	Responsible for handling incoming and outgoing traffic directed either towards tier 1 or tier 3. Incoming flows are parsed, and based on their origin and content are dispatched towards the respective component for further processing. Upon completion, the internal components notify the Application Service Handler for forwarding the information towards the final destination (tier 1 or tier 3).
Gateway	
Databases	Storage of all HYDROBIONETS platform information and the information related to the existing sensors. Interacts in a bidirectional manner (read / write) with the Visualization component, the OPC Client and the Gateway.
Visualization tool	
Server	Interaction point between the current (wired) system and the HYDROBIONETS system. This allows interaction with the current communication system, sharing the required data without modifying the PLC or SCADA, thus making the interaction safe for the current system and reducing the amount of duplicated effort.
Software tools	Set of programming languages and database management packages used to implement the front-end and the back-end of the visualization platform (Apache 2.x, PHP (≥ v5.4), MySQL 5.x, Java 1.7.x).
Control and actuation	
Biocide pump	Once the measurements of biofilm sensor exceed the threshold, the biocide pump receives the control command from OPC client and starts dosing. The frequency of the pump is controlled such that the dosage meets a set point.
Sodium bisulphite pump	Based on the data reading of chlorine sensor installed before the reverse osmosis membrane, the set point for the Sodium bisulphite pump is calculated by the OPC client. Sodium bisulphite is dosed to neutralize the chlorine.

Chemical backwash	When the data of biofilm sensor indicate that the activation threshold has been reached, chemical backwash in the ultrafiltration system starts. The filtered water that is stored in backwash tank is then released for membrane backwash. In addition, an alert is generated.
Cleaning in place	When measurements of biofilm sensor reveal that the corresponding threshold has been reached, cleaning in place in the ultrafiltration system starts. The filtered water that is stored in backwash tank is then released for membrane backwash. In addition, an alert is generated.

4. Overall system architecture

The following figures describe how the distribution of the sensors would be achieved in the various different areas of a large-scale desalination plant. Total area to be covered could be up to 78,000 m^2.

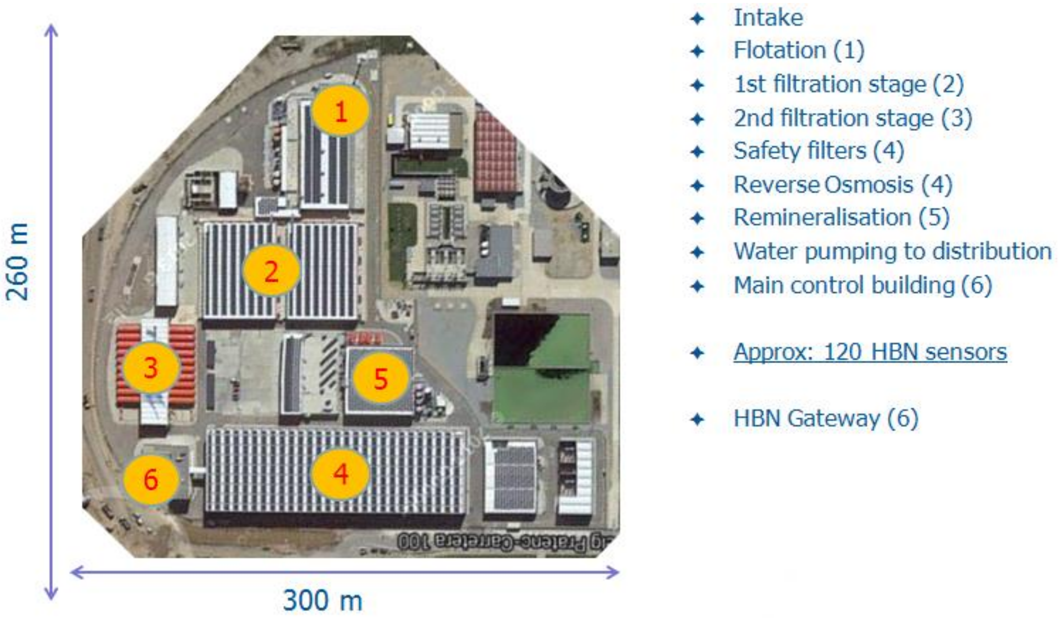


Figure 1: HYDROBIONETS sensor locations in a desalination plant.

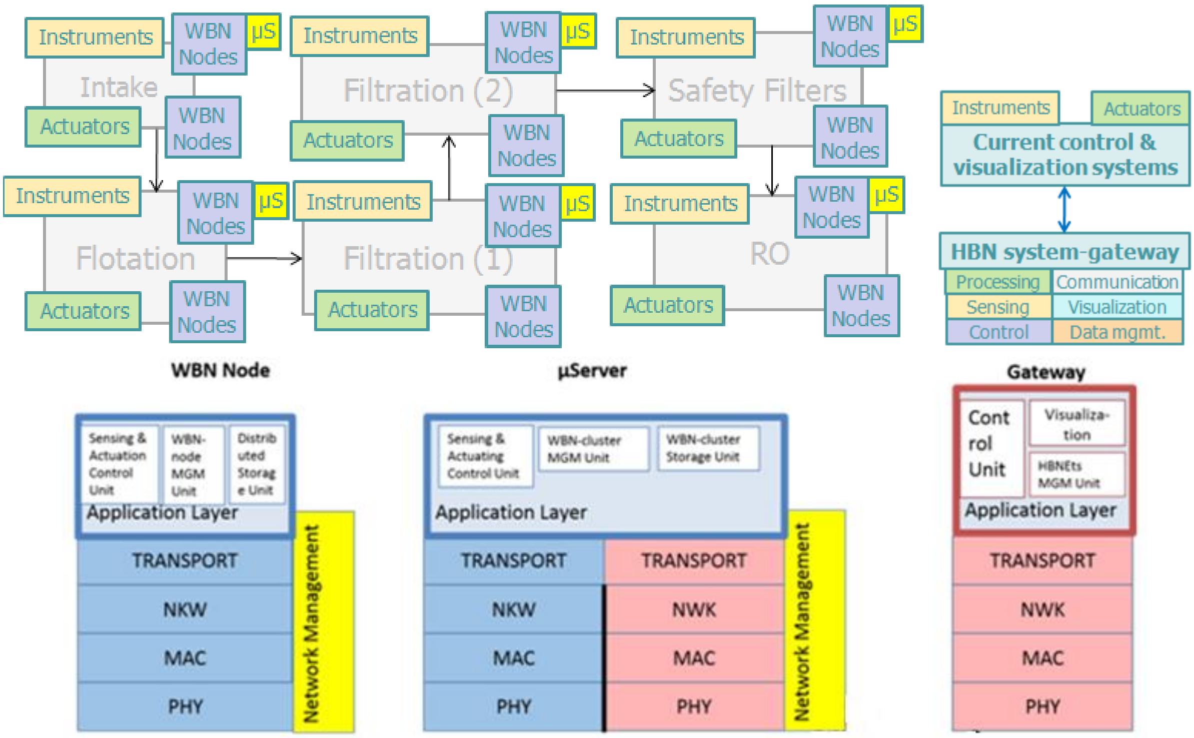


Figure 2: *Communication and control architecture for HYDROBIONETS system.*

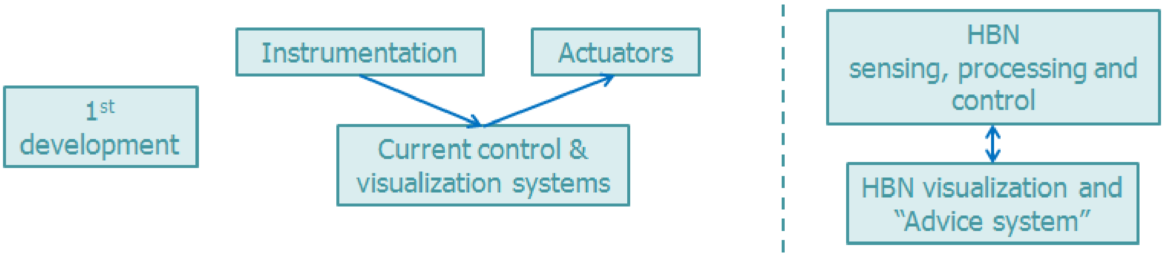
5. Integration of the system with water treatment facilities

There are a number of integration options which can be considered for a full-scale HYDROBIONETS system. These integration possibilities can act as well as a staged development of the system in the route to market.

5.1. Decision support tool

In this option, the HYDROBIONETS system provides advice based on external learning (demonstration phase learning). It is basically a Decision Support tool with the following features:

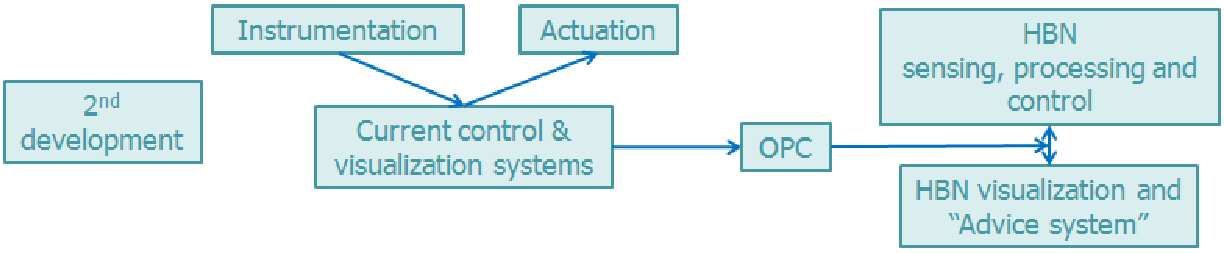
- The full-scale plant manager is able to interact with the HYDROBIONETS system, introduce current plant data and state.
- Based on the advice given by the HYDROBIONETS system, the plant manager can modify the operation of the full-scale plant and take decisions.
- This option can be considered for both current plants and new installations.



5.2. Improved decision support tool

In this option, the HYDROBIONETS system receives information from the existing plant systems to improve the advisory capacity. It is an Improved Decision Support tool.

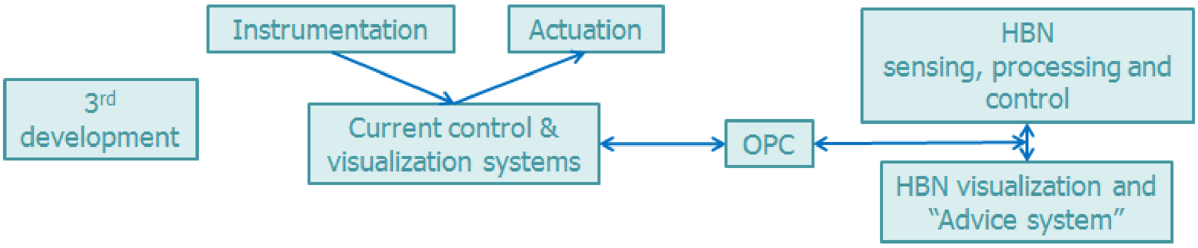
- Through an OPC, the HYDROBIONETS system receives real-time data from the full-scale plant system. This improves the prediction capabilities.
- Based on the advice given by the HYDROBIONETS system, the plant manager can modify the operation of the full-scale plant and take decisions.
- This option can be considered for both current plants and new installations.



5.3. Cooperative Smart System

In this option, the HYDROBIONETS system communicates with and receives information from the existing plant control system. It has the capacity to take decisions and improve the plant operation autonomously.

- The full-scale plant manager is able to interact with system by consulting the HYDROBIONETS visualization system.
- The plant manager can accept the suggestions, and modify the operation of the full-scale plant, or can even leave the system act automatically.
- This option can be considered for new installations, or for current plants that conduct extensive modifications of the control systems.



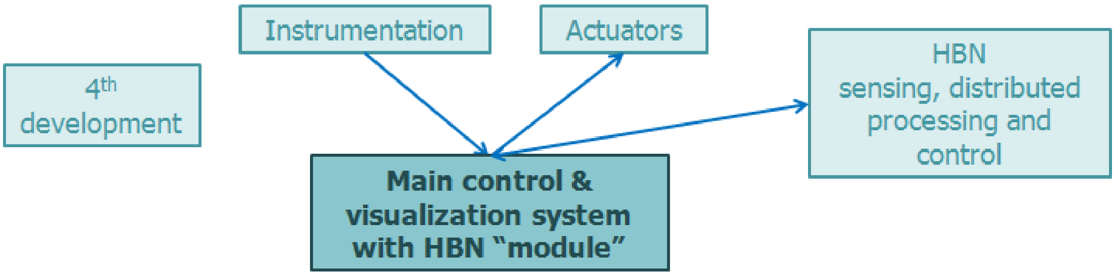
5.4. Integrated Smart System

In this final option, the HYDROBIONETS system is fully integrated in the full-scale plant. It has the capacity to take decisions and improve the plant operation autonomously.

- The full-scale plant manager is able to interact with HYDROBIONETS system directly in the main control and visualization systems of the plant.

- The plant manager can accept the suggestions, and modify the operation of the full-scale plant, or can even leave the system act automatically.

This option can only be considered for new installations, or extensive refurbishments of existing plants.



6. Description of the sensors

The sensors chosen are interdigitated, because of their well-known high detection sensitivity due to the higher working surface in comparison with other sensors of the same area. This working surface is made of Tantalum Silicide ($TaSi_2$), covered with a silicon oxide (SiO_2) thin layer. This material is a semiconductor, and due to this and the covering layer, we avoid any possible oxidation problem.

The chips are fabricated in CMOS technology and each of them has 4 sensors (Figure 3). With this configuration, we are able to have 4 different replicas at the same time and also, depending on the cell, to measure different media simultaneously.

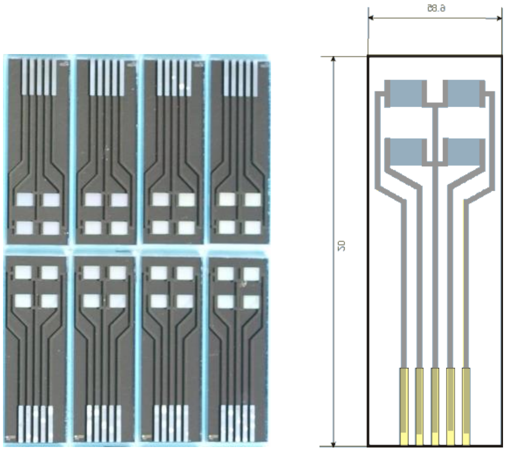


Figure 3: Scheme and picture of chip.

To increase the reproducibility of the measurements and have more control of the data we have fabricated a Printed Circuit Board (PCB) especially designed for the chips. With these PCBs we have not only a higher reproducibility but they also allow us to locate the sensors away from the contacts connected to the electronics, increasing the functionality of the mote. This PCB connects the chip with an USB connector and the contacts are protected with a resist to avoid any damage due to humidity or any external factor (Figure 4).

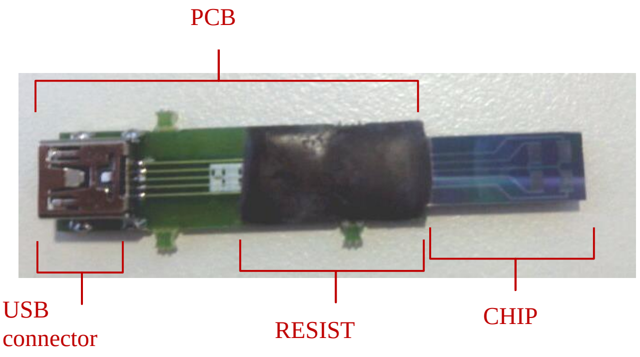
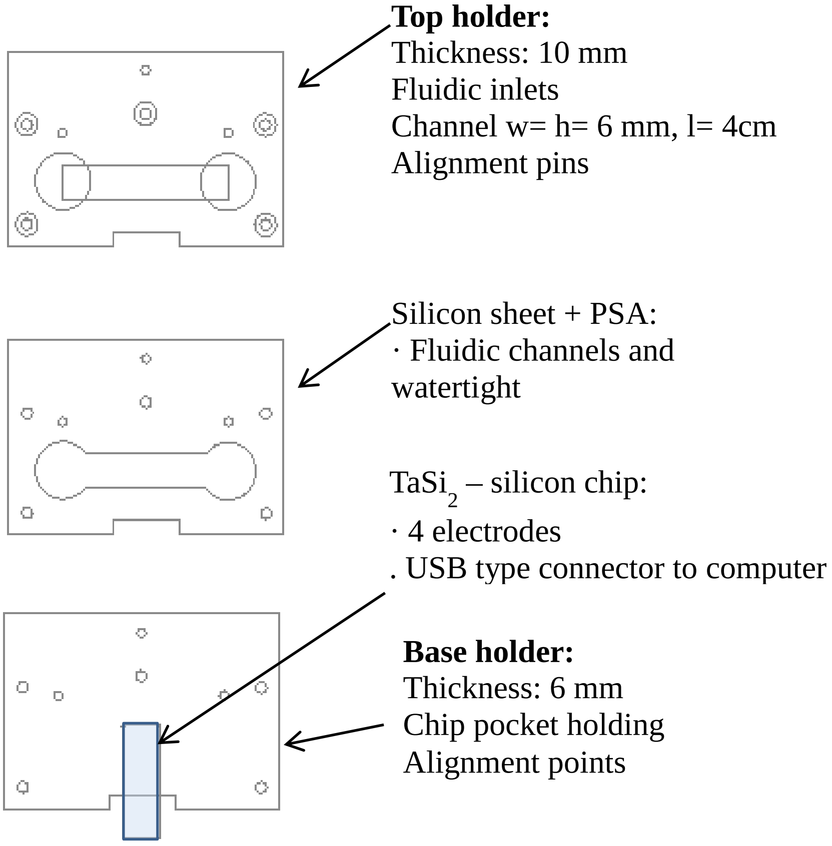


Figure 4: Picture of the sensor chip encapsulated in the PCB fabricated.

6.1. Description of the sensor cell

The cell designed for the plant is made basically of methacrylate (PMMA). This cell is designed to support higher flow and pressure compared with the previous ones designed for laboratory tests. The dimensions of the cell are 34 x 50 mm and it is composed of two pieces of PMMA. The top holder has a thickness of 10 mm and contains the pipe itself. The pipe is a square channel of 6 x 6 mm cross-section and 4 cm long. The base holder has a thickness of 6 mm and a notch to hold the chip. Between these two pieces there is a PDMS sheet 300µm thick glued with Pressure-Sensitive Adhesive (PSA) material. This sheet avoids any possible leakage between the interconnecting parts. The sensor cell configuration can be seen in Figure 5. A picture of a mounted sensor cell is shown in Figure 6.



Top holder:
Thickness: 10 mm
Fluidic inlets
Channel w= h= 6 mm, l= 4cm
Alignment pins

Silicon sheet + PSA:
· Fluidic channels and watertight

$TaSi_2$ – silicon chip:
· 4 electrodes
. USB type connector to computer

Base holder:
Thickness: 6 mm
Chip pocket holding
Alignment points

Figure 5: Schematic of the plant sensor cell.

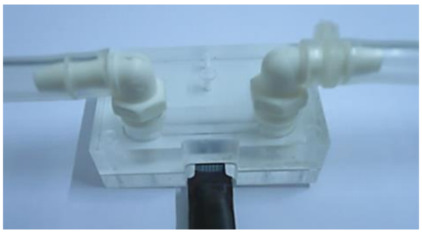


Figure 6: Picture of the new sensor cell for the pilot plant.

6.2. Data acquisition

The strategy used for continuous monitoring of biofilms was the electrochemical impedance spectroscopy (frequency-dependent resistance to the flow of current). The data is analyzed with an equivalent circuit that we have been able to simplify to just a capacitance and a resistance in serial.

With this model we can follow the data evolution with the presence of the bacteria and represent it throughout time. . The presence of bacteria will modify these two parameters at a given frequency, that we can chose at our convenience, one for each parameter (Figure 7).

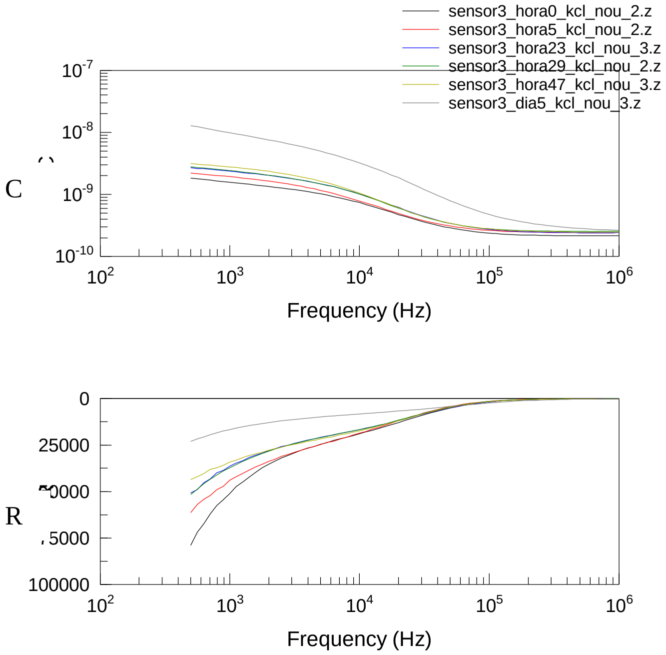


Figure 7: Capacitance and Resistance representation with time in bacteria presence (between 0 to 5 days of measurement).

As can be seen, taking into account clear change of the values of the parameters, the sensor response follows the presence of the bacteria, and this way, any change in the sensor surface can be registered just taking into account the variation of two parameters: C and R.

If we fix one frequency for each of the parameters we can represent these parameters versus time.

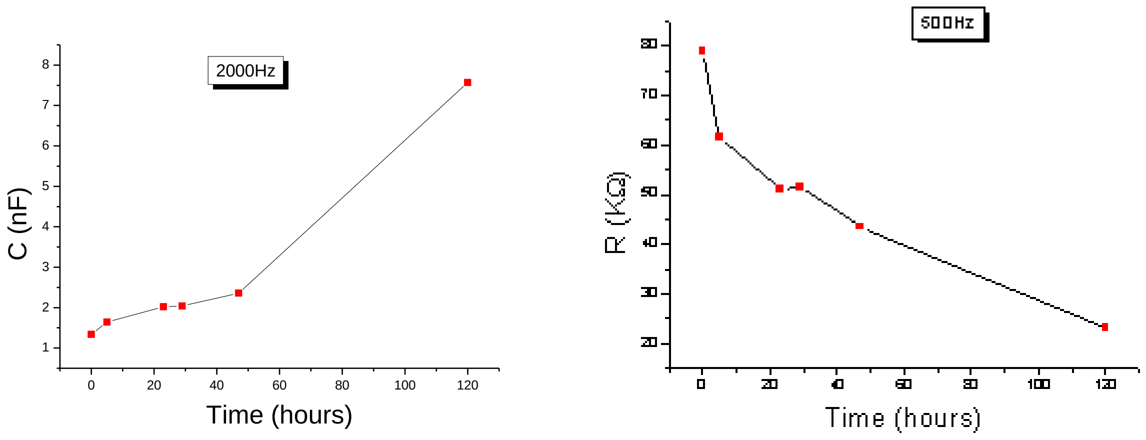


Figure 8: Capacitance and Resistance representation with time for a fixed frequency.

6.3. Specifications of the sensor module

The HYDROBIONETS sensor module will have to address the following general requirements:

- Embedding the biofilm sensor described above into a fully autonomous measurement module
- Fluidic interface between the existing desalination plant and the sensor cell
- Maintenance-free operation for 2 months
- External dimensions: up to 30 x 30 x 20 cm
- Wireless data transfer for up to 10 measurements per day

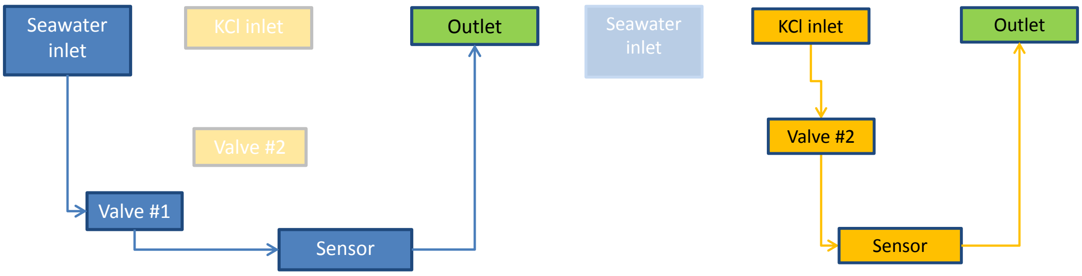


Figure 9: The block diagram of the measurement (standby and measurement modes).

The basic concept of the biofilm thickness measurement is the following:

The sensor modules will be placed at the specified spots of each treatment channel by means of a bypass, so that the sensors are not placed at high pressure zones of the system. In standby mode, the inlet water passes through the sensor, so the biofilm can grow, as would normally happen on the inner surface of the system pipes.

However, the impedance measurement is not possible in the presence of seawater because of: 1) its high conductivity and 2) the time-variance of the salinity and permittivity of the water. Hence, a specific media, KCl is introduced in the system for the brief period of the measurement. This liquid ensures a low conductivity media around the sensor surface and its electromagnetic properties are constant in time.

In order to achieve these objectives, a sensor module containing the following sub-systems was developed:

- Sensor electronics
- Fluidic system
- Measurement control electronics
- Microcontroller unit
- Wireless communication module

6.3.1. Sensor electronics

The biofilm thickness will be measured by the investigation of the impedance of the sensor presented above. As described, the actual impedance of the sensor can be modelled by a series R-C circuit. According to the principals of the sensing element the optimal measurement frequency is different for the resistive (R) and for the capacitive (C) part. The resistive component will be determined from the impedance spectrum below 1 kHz while the capacitive part will be concluded from the spectrum above 1-40 kHz.

For this purpose a wideband impedance spectroscopy was developed that can measure the sensor impedance in this frequency range. The impedance spectroscopy electronics is based on the SoC solution of Analog Devices (AD5933). The analog front-end consist of as less components as possible in order to maintain the power consumption at a minimal level. It is based on a high precision dual operational amplifier (AD8606). The output stage has dual purpose: to keep the output impedance of the impedance analyzer SoC at a constant low level (in voltage follower mode). This is required because the AD5933 chip has a varying output impedance according to the different output voltage levels between 200 and 2400 Ω. This can have a serious effect on the measurement accuracy. The output impedance of the AD8606 buffer amplifier in follower mode can be kept below 1Ω below 100 kHz. Besides the DC offset of the AD5933 also varies regarding the output modes. First, the DC level is decoupled and at the op-amp it is set to the half of the voltage reference (to 1.5 V). The peak-to-peak voltage of the output signal is adjustable between 0.2 and 2 V.

The input stage is a current-to-voltage amplifier that minimizes the input bias current of the receiver and set the overall loop gain by the C-V feedback resistor.

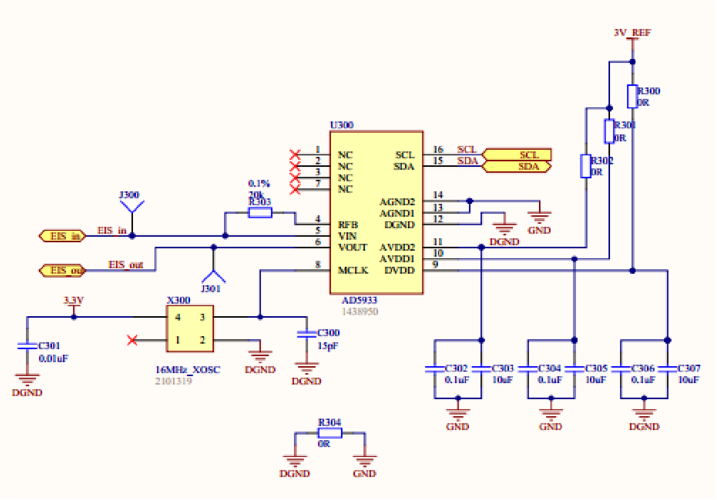


Figure 10: *Schematic of the impedance spectroscopy electronics.*

Between the output and input stages, three low resistance SPDT switches (ADG819) were included. The purpose of these switches is to change between the calibration and the measurement modes and to select between the two calibration components and the two sensing elements included in one channel of the sensor. In this way, the entire measurement is fully autonomous, it can calibrate itself and carry out the impedance analysis of the two sensing element. The two known calibration components (a resistor and a capacitor) are placed on-board, while the sensing elements are interfaced by a mini-USB connector.

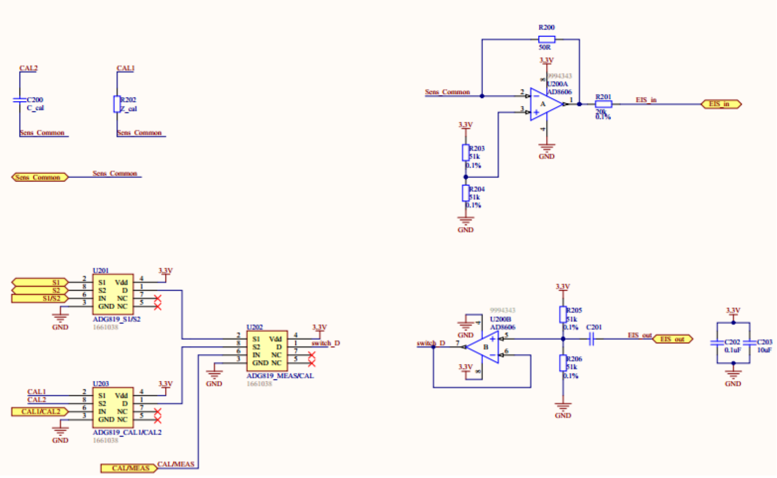


Figure 11: The analog front-end of the sensor electronics.

6.3.2. Fluidics system

6.3.3. Control electronics, communications

The next two main sub-modules of the sensor module are the measurement control and the wireless communication. In order to minimize the power consumption and the real estate in the sensor module an MSP430 based microcontroller integrated with a CC2420 wireless transceiver module was selected. The XM1000 module incorporating these components was selected according to the following specifications:

Proc. Model	TI MSP430 F1611/ TI MSP430F2618
Memory	10 KB SRAM/ 8 KB SRAM
	48 KB Flash/ 116 KB Flash
	1 MB serial Flash (data logger)
Interfaces	UART,SPI, I2C, 16 GPIOs/ UART,SPI, I2C, USB, 32 GPIOs
Frequency	8 MHz/ 16 MHz
RF Chip	TI CC2420
Frequency band	2400 – 2483.5 MHz
Sensitivity	-95 dBm
Data rate	250kbps
RF power	-25 -- 0 dBm
Range (typ.)	up to100m (in), 50m (out)

The XM1000 runs the Contiki real time operational system. The measurement control firmware (both electronics and fluidics) and the communication protocols are developed in Contiki.

Besides the microcontroller based sub-system the control electronics includes a two-channel valve driver for the fluidics control. Each channel can drive a load of up to 300 mA at 12 Volt.

7. Network and control specifications

7.1. The BioMEM Network

In this section we elaborate on the design of the BioMEM network architecture and protocol stack. The main requirements considered for the design are:

- Scalability in terms of number of BioMEM and other wireless sensor and actuator nodes.
- Energy efficiency for the entire network to maintain low operation costs and low energy consumption at the battery operated nodes for long network lifetime.
- Adaptability of the possibly harsh wireless environment in the industrial plant.
- Interoperability with the existing system.

To allow efficient and also flexible communication in the large-scale industrial plants, we propose a network architecture where three different levels (tiers) of nodes are specified, as shown in Figure 12. The nodes in the different levels have significantly different computational and communication capabilities, and play different roles in communication, processing and control.

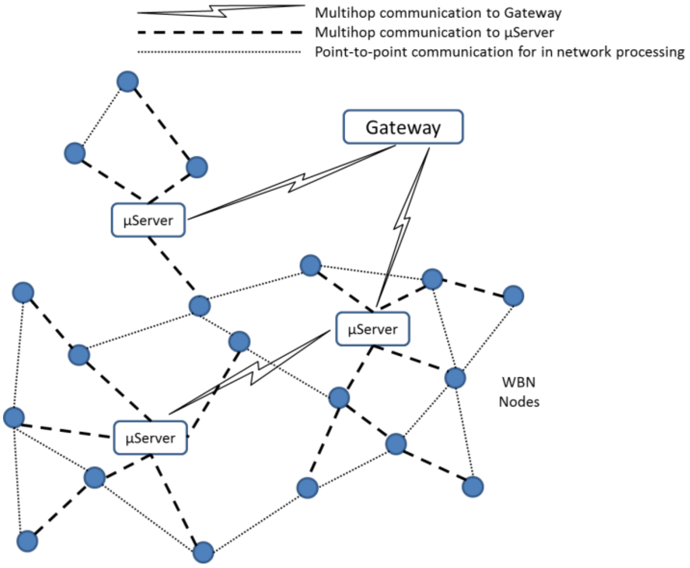


Figure 12: Three tier architecture.

Tier 1 is formed by the WBN nodes. These devices are expected to have a limited processing and memory capability, a limited transmission range and a low cost (examples for such nodes are Telosb, Iris or MicaZ models). The main tasks of the Tier 1 devices are: (i) direct communication with other WBN nodes; (ii) direct or multi-hop communication with the corresponding second tier node, that is, the µserver; (iii) the partial storage of information; and finally (iv) participation in in-network computation for distributed sensing and control.

Tier 2 is composed of the µservers. These are more complex devices, with more storage, processing and communication abilities, and support both communication and in-network processing. These devices are in charge of critical decisions, such as analyzing the different concentration parameters and activating the corresponding actuators; keep sensing and actuation configuration parameters, such as different threshold values, dosage quantities and others; and are responsible for calibrating the WBN nodes. Apart from communicating with the related WBN nodes, they forward the gathered data towards the central controller.

Tier 3 involves the gateway or gateways that provide connectivity to the BioMEM network.

The proposed protocol stack per building unit is summarized in Figure 13. The architecture contains all layers involved in the data transmission in a typical networked system, starting from the physical (PHY) layer, up to the transport layer. Moreover, driven by the need for graceful self-adaptation of the network components within both Tiers 1 and 2, we defined a vertical network management plane, capable of interacting with all network layers. The network management plane supports all network management functionalities and assists cross-layer solutions in Tiers 1 and 2. In addition, the design of the Application Layer considers the different high-level components that correspond to either co-depended or unrelated functionalities of the BioMEM platform.

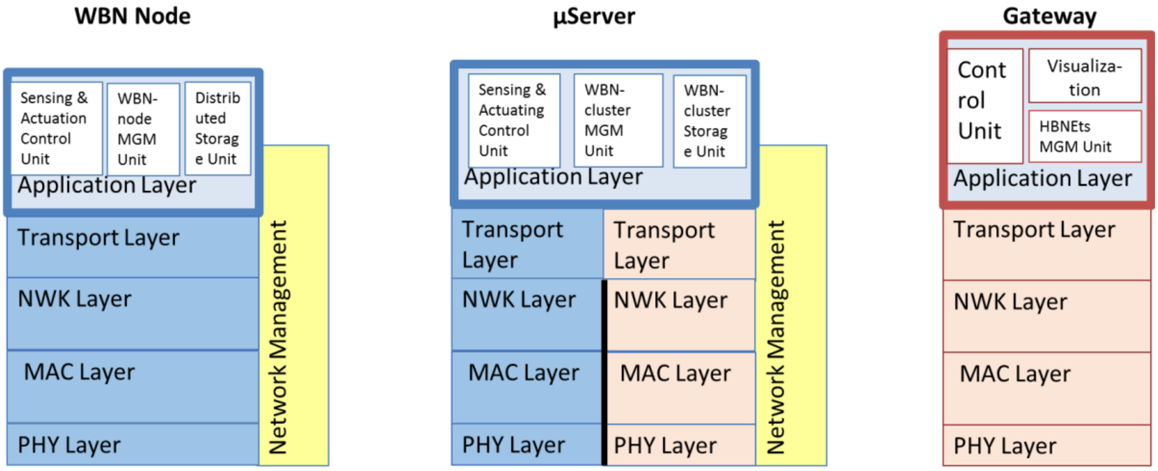


Figure 13: BioMEM network protocol architecture.

7.2. The WBN Node protocol stack

Considering the description scenario and system requirements (given in Deliverable D2.2,) the proposed protocol stack of the WBN nodes indicates the functionality of a multi-hop network that forms a tree-based topology for information fusion and central control as well as a mesh topology for in-network data processing.

- Physical (PHY) Layer: It employs the well-studied IEEE802.15.4 compliant low-level modules and allows node reconfiguration. The objective of the PHY layer is to enhance the reliability of the physical links and improve node to node communication. Therefore, in conjunction to the vertical Network Management plane, it allows node adaptation, e.g., frequency and transmission power selection. Such functionality is important since the HYDROBIONETS WBN operates in an industrial environment that manifests various radio propagation phenomena (e.g., shadowing, multipath, noise and interference), which may cause severe performance degradation. Moreover, frequency selection is critical due to the coexistence of several Tier 1 “clusters” and also the Tier 2 network nodes. The control of transmission power is necessary not only for reliable node to node communication but also for the proposed MAC protocols.

- Medium-Access Control (MAC) Layer: With regard to the MAC Layer, we propose CSMA/CA mechanism for accessing the medium. This solution is designed to avoid the control overhead present in time division (TDMA) based solutions (synchronization, etc), as well as the overhead due to explicit collision avoidance mechanisms. Additionally, this solution and is efficient enough to work in massive traffic scenarios like deployments in full-scale plants. The standard CSMA/CA access control is extended with **Noise Thresholds,** such that, each node knows, for each potential receiver node, the maximum power level that can be present in the channel while ensuring a correct reception at the receiver.

  Thus, whenever a node has a packet to transmit, it periodically checks the channel (with a period length given by the parameter **Contention Window**) and compares the power level in the channel with the **Noise Threshold** corresponding to the intended receiver. The transmission occurs when the power level in the channel is smaller than the threshold. Currently, the **Noise Thresholds** are calculated and pre-loaded in the nodes offline. The standard CSMA is also enhanced with transmission power optimization to adapt the achievable throughput of the links to the possibly unbalanced traffic load. Figure 14 demonstrats the expected performance gain of the adaptive threshold based CSMA.

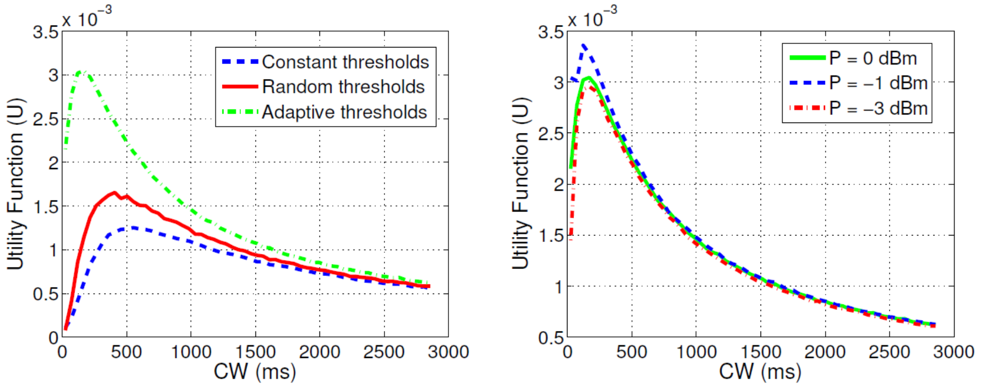


Figure 14: Threshold based CSMA Utility function compared to SoA for transmission power P=0dBm and the utility of the Adaptive threshold solution for different transmission power levels.

In addition, in case the Tier 2 traffic is significant and interferes with the transmissions of the WBN nodes, the COG-MAC access control applies extended channel sensing and packet size optimization to avoid the Tier 2 interference. The packet size optimization allows for Tier 1 packet sizes to fit into the idle periods in the Tier 2 communication. The extended channel sensing makes sure that Tier 1 communication does not start in the short back-off periods, typical in IEEE 802.11, to be applied in Tier 2. As shown in Figure 15, COG-MAC can decrease both the energy consumption and the delay by allowing short multihop paths even under Tier 2 interference.

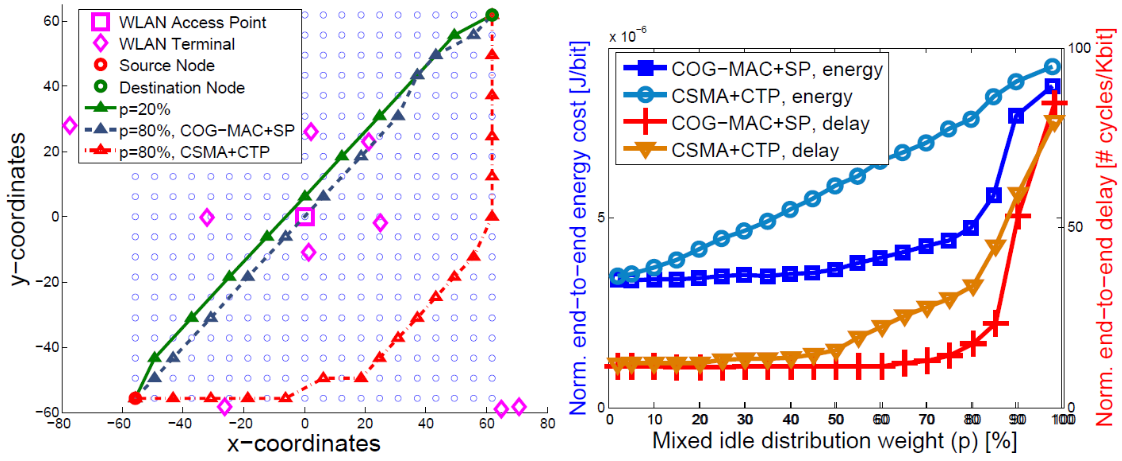
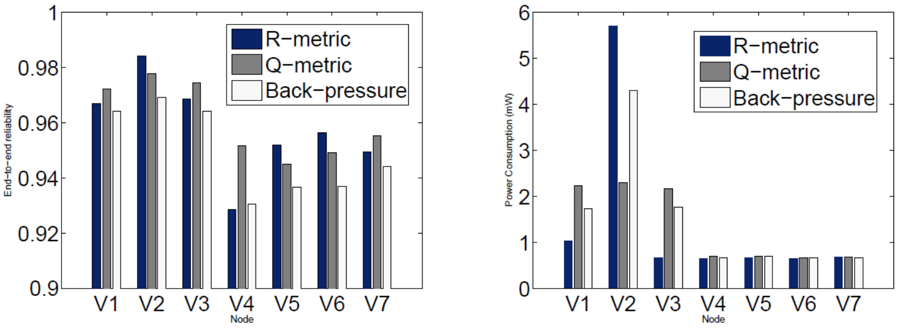


Figure 15: Cognitive MAC (COG-MAC) to avoid Tier 2 interference. The minimum energy routing paths for standard CSMA/CA and for COG-MAC, and the resulting delay and energy cost, for different Tier 2 traffic characteristics.

- Network (NWK) Layer: Within tier 1 the NWK layer is responsible for establishing the routes between: (a) pairs of WBN nodes for in-network processing or control; (b) WBN nodes and the µserver for information fusion or distribution, network management and bi-link information transfer. The basic NWK mechanism is the RPL, which is the IETF routing protocol for low power lossy networks. The selection of RPL as the default for the protocol stack of the WBN node is in compliance with the CSMA/CA mechanism considered for the MAC layer. We suggest enhancing the RPL protocol by new routing metrics that allow more complex design objectives. Specifically, the proposed routing metric is based on locally observable parameters and achieves load balancing under data transmission performance constraint, posed by the control and actuation.

  We propose a modular implementation such that the new routing metrics can be easily implemented. The performance of the proposed Q-metric is shown in Figure 16.



(a) (b)

Figure 16: RPL with various routing metrics. The proposed Q-metric balances the ene4rgy consumption with slightly increased end-to-end delay.

- Transport Layer: The definition of the Transport Layer within Tier 1, providing UDP or TCP-based end-to-end transmission control, can promote interoperability for the network high-level services. This allows the establishment of a communication path between the WBN nodes and the µserver, or the WBN nodes and the Gateway, depending on the application, or from WBN node to WBN node across one or more µserver. That is, the endpoint of the TCP/UDP connection depends on the application. The strength of this approach is that it allows configuring the control and actuating units as application ports. However, the additional layer will, in turn, introduce an additional packet header, and thus traffic overhead, the highly varying PHY layer conditions may lead to increased Transport layer control traffic and in the case of TCP also low throughput. Consequently, the Transport Layer can be optional.
- Application Layer: The Application layer encompasses three main components namely: (a) the Sensing and Actuating Control Unit, (b) the WBN node Management Unit, and (c) the Distributed Storage Unit. The Sensing and Actuating Control Unit is responsible for data acquisition and pre-processing. This unit is responsible as well for the distributed in-network data processing and control. The WBN Management Unit focuses on the sensors self-cleaning and calibration, the WBN-nodes reprogramming functionalities and the sampling frequency

optimisation. Finally the Distributed Storage Unit is responsible for the distributed data storage application.

To support in-network data processing, we propose optimized solutions for distributed computation, based on optimal link selection and power control. We propose solutions for the scenario where the density of the µservers is large, and the distributed consensus algorithms can utilize Tier 2 transmission resources and the case where there is no Tier 2 support and the Tier 1 nodes have to optimize their transmissions. We show that by optimising the network topology with the tools of power control and link selection, both the consensus delay and the energy consumption can be decreased. The achievable gain depends on the radio environment, as shown in Figure 17.

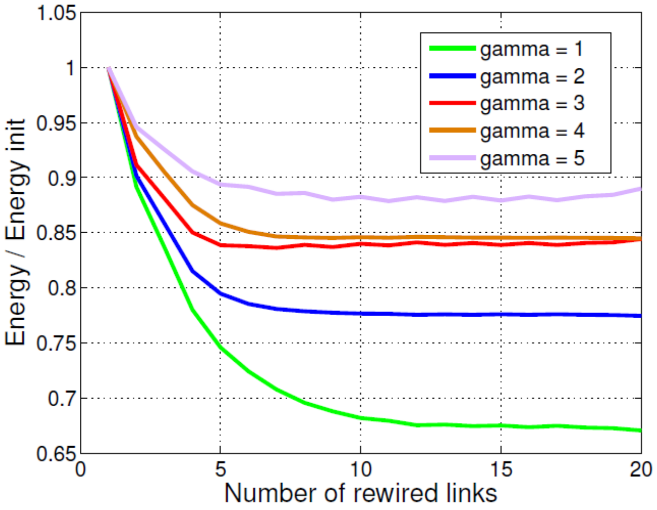


Figure 17: Energy consumption of distributed consensus with optimal rewiring.

7.3. The microserver protocol stack

The µserver is responsible for enabling the communication between Tier 1 and Tier 2, and for collecting information for the network management mechanism. Moreover, the µserver coordinates a group of WBN nodes (cluster) and is in charge for network configuration, management and adaptation mechanisms, and implements the functionalities that cannot be directly supported by a WBN node. The component Sensing and Actuating Control Unit is responsible for applying sophisticated interpolation techniques that facilitate the in-network processing within Tier 1, and for calculating and distributing optimal weights for distributed algorithms. The WBN-Cluster Management Unit undertakes functionalities related to the over-the-air programming, self-cleaning and transmission frequency adaptation, for the entire WBN cluster. Similarly, the WBN-Cluster Storage Unit is responsible for coordinating the associated WBN Distributed Storage Units.

Compared to the WBN nodes, the µserver has increased transmission and computational power and storage capacity. Due to the different requirements and capabilities of nodes within Tier 1 and Tier 2, the Tier 2 µserver implements two protocol stacks, one for communicating with the Tier 1 WBN nodes, based on IEEE802.15.4 and following the stack described previously, and one for Tier 2 communication with other µservers and gateways, allowing standard IEEE802.11 infrastructure-less mesh communication.

7.4. The Gateway protocol stack

The Gateway serves as the end-point between the BioMEM platform and the existing infrastructure. On the wireless side, it implements µserver IEEE802.11 protocol stack. It interacts with the existing infrastructure through the application layer. The systems administrator manages the system and network via the functionalities provided by the following units of the Application Layer: (a) the Control Unit, which is responsible for the high-level control commands and the monitoring of the bio-fouling procedures; (b) the HBNnet MGM Unit, which is responsible for the overall network management of the BioMEM platform; (c) the Visualization Component, enables the visualization of the different aspects of the system (biofouling, network status, etc.).

7.5. The Network Management Plane

The definition of the on-node Network Management plane is motivated by the RF-hostility of the industrial environment and the criticality of the data collected by the industrial plant. Its objectives are to detect failures and performance degradation and feed this information to the system administrators. Moreover, it provides a well-structured way to support cross-layer protocol design in the WBN node. The Network Management is responsible for: (a) the network monitoring, measurement collection, and processing; (b) the communication between different components of the system architecture; (c) the reporting and events logging; and (d) the adaptation and failure management. For this purpose, the corresponding component collects information about the operational channel of the WBN clusters, the battery lifetime and resulting energy costs, the transmission power, the bit rate, the input power and corresponding signal-to-(interference plus)-noise ratio (S(I)NR), and the link quality indicators. This information is communicated either in the form of periodic, dedicated beacon messages, or piggybacked in the data packets, and can be fed to the remaining layers of the WBN protocol stack.

7.6. Implementation of the BioMeM Protocol Stack

Whilst the design of the BioMEM network platform and the accompanying characteristics of specific protocol layers are briefly described in the section above, we will in the following paragraphs provide the specifications for the implementation and testing of the BioMEM protocol stack.

7.6.1. Specifications for the implementation of the WBN Node

The WBN node protocol stack mainly comprises of three novel components: (a) the Network Management Component, responsible for implementing the Network Management Vertical Plane; (b) the Link Scheduling Component, responsible for implementing the Threshold Adaptive CSMA protocol; (c) the MAC-aware RPL component, responsible for implementing the MAC-aware routing mechanisms. Figure 18 describes both the location of each component within the protocol stack, as well as their interconnections.

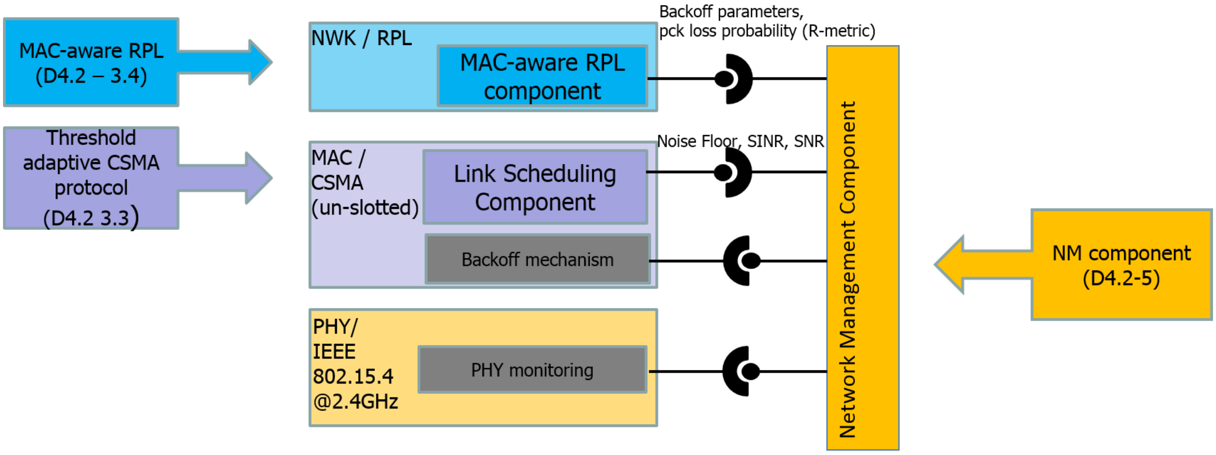


Figure 18: The WBN Node intra-node component diagram

In specific, the Network Management Component, collects information from the Physical Layer about the signal strength, link quality and noise levels and provides it as an input to the Link Scheduling component. Similarly, based on the CSMA mechanism of the MAC layer, the Network Management Component collects information on the backoff parameters and the packet loss probability and provides it as an input to the MAC-aware RPL component.

Based on the proposed intra-node component diagram, the implementation of the WBN node can adopt a highly modular approach. Testing the functionalities of the integrated protocol stack can exploit this modular approach, by initially considering that only the Network Management component is active, then combining it with the Link Scheduling Component, and finally integrating on top the MAC-aware RPL component.

7.6.2. Specifications for the implementation of the microserver

The µserver is implemented as an Application Level Gateway. As shown in Figure 19, it adopts a Provider – Consumer design pattern. This allows us to efficiently handle different types of incoming traffic and, depending on the data type and content, derive the desired outcome towards the desired destination. As a result, the core of the µserver uses the same type of methods and buffers to handle incoming traffic regardless of whether it is originated from tier 1, tier 2 or tier 3. This approach additionally allows portability in adding sophisticated components that are essential for decentralized operation of the BioMEM platform, such as the Sensing and Actuating Control Unit (for in-network processing and inference), the WBN Distributed Storage unit and the WBN Cluster MGM unit (Network Management).

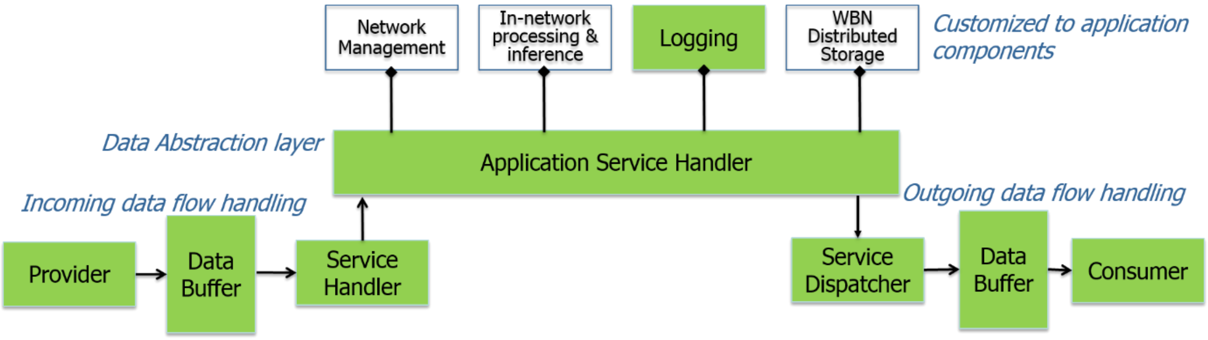


Figure 19: Intra-component diagram for the µserver. Components in green illustrate the core of the µserver, and components in white the components that can be added, with respect the application requirements.

The core of the µserver is implemented as a multi-threading system. A preliminary version of the class diagram is presented in Figure 20. As is shown, the main system threads are dictated by the network interfaces of the µserver, namely its communication with the WBN nodes (Serial Comm) and with the Gateway (GatewayComm). Nevertheless, regardless of its origin, incoming traffic is converted in an abstract type of data ("Packet"), and is treated according to its contents, its source and destination.

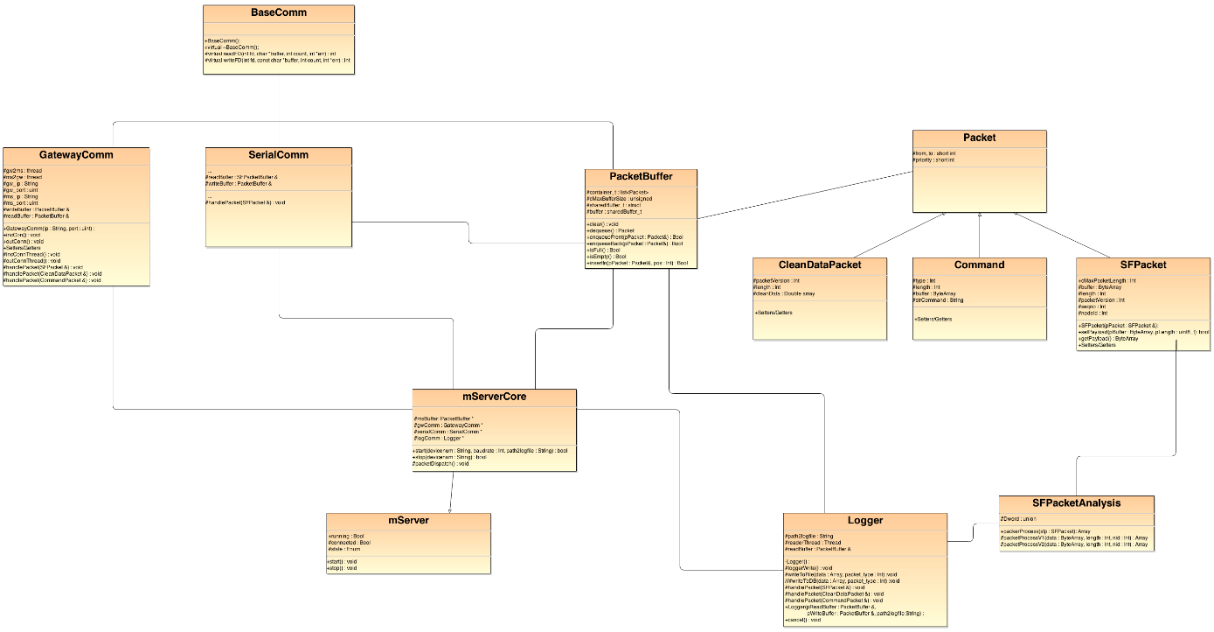
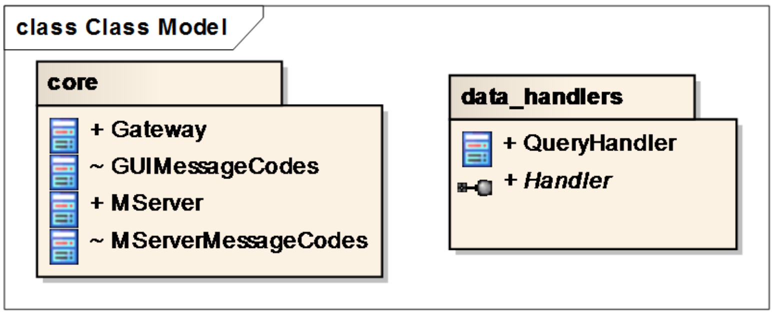


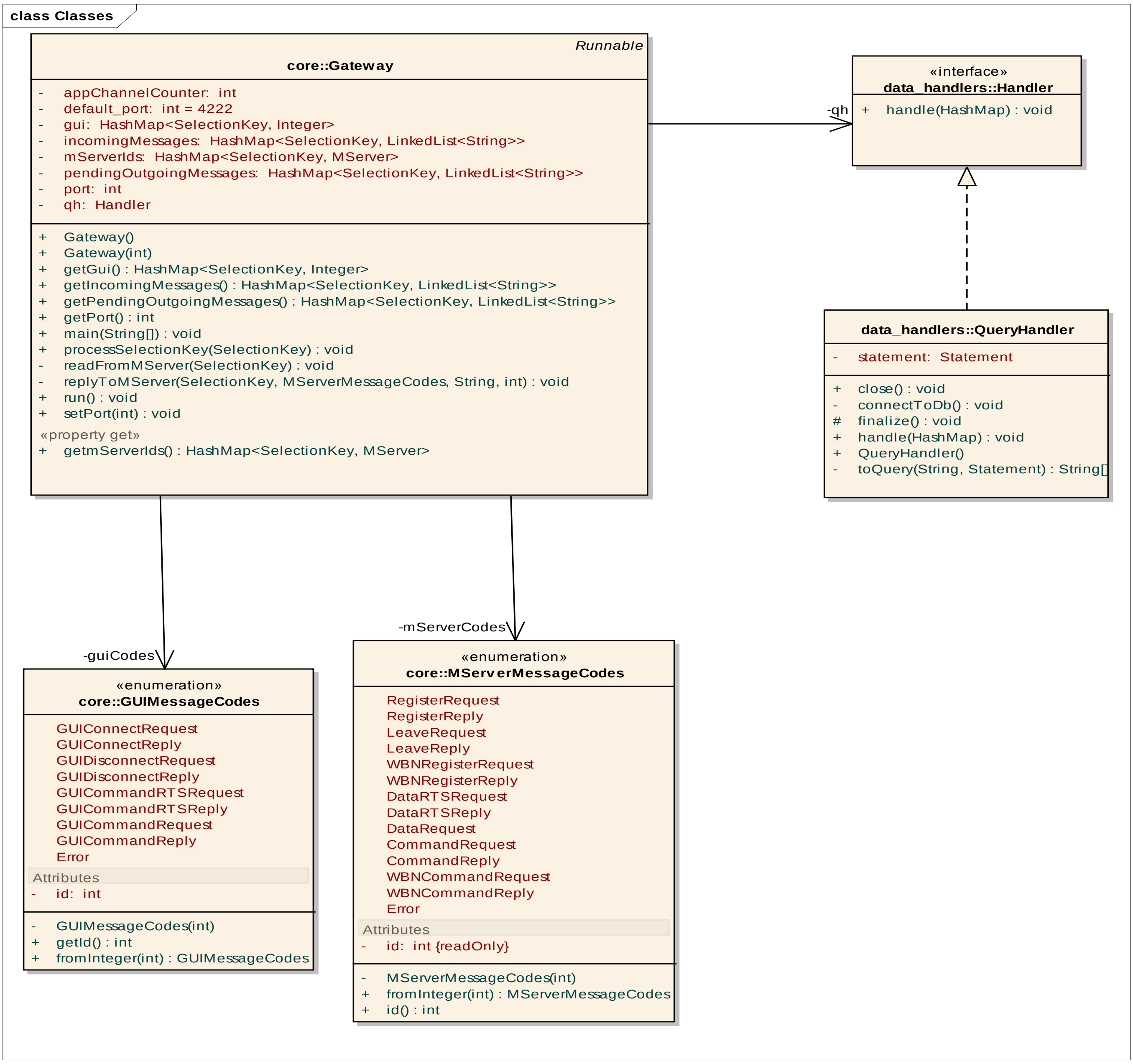
Figure 20: Preliminary class diagram of the µServer core.

7.6.3. Specifications for the implementation of the Gateway

While the Gateway has similar functionalities as those of the µserver, it has a more centralized role, as it is responsible for interconnecting the User Interface with the BioMEM platform. In addition, in a large-scale deployment the Gateway should efficiently handle concurrent queries from multiple µservers.

From an implementation perspective, the Gateway relies on the Selectors design pattern, which enables parametric modelling highly interactive systems. A preliminary class diagram of the Gateway is provided in Figure 21.


class Class Model
core
+ Gateway
~ GUIMessageCodes
+ MServer
~ MServerMessageCodes
data_handlers
+ QueryHandler
+ Handler


class Classes
Runnable
core::Gateway
- appChannelCounter: int
- default_port: int = 4222
- gui: HashMap<SelectionKey, Integer>
- incomingMessages: HashMap<SelectionKey, LinkedList<String>>
- mServerIds: HashMap<SelectionKey, MServer>
- pendingOutgoingMessages: HashMap<SelectionKey, LinkedList<String>>
- port: int
- qh: Handler
+ Gateway()
+ Gateway(int)
+ getGui() : HashMap<SelectionKey, Integer>
+ getIncomingMessages() : HashMap<SelectionKey, LinkedList<String>>
+ getPendingOutgoingMessages() : HashMap<SelectionKey, LinkedList<String>>
+ getPort() : int
+ main(String[]) : void
+ processSelectionKey(SelectionKey) : void
- readFromMServer(SelectionKey) : void
- replyToMServer(SelectionKey, MServerMessageCodes, String, int) : void
+ run() : void
+ setPort(int) : void
«property get»
+ getmServerIds() : HashMap<SelectionKey, MServer>
-qh
«interface»
data_handlers::Handler
+ handle(HashMap) : void
data_handlers::QueryHandler
- statement: Statement
+ close() : void
- connectToDb() : void
finalize() : void
+ handle(HashMap) : void
+ QueryHandler()
- toQuery(String, Statement) : String[
-guiCodes
«enumeration»
core::GUIMessageCodes
GUIConnectRequest
GUIConnectReply
GUIDisconnectRequest
GUIDisconnectReply
GUICommandRTSRequest
GUICommandRTSReply
GUICommandRequest
GUICommandReply
Error
Attributes
- id: int
- GUIMessageCodes(int)
+ getId() : int
+ fromInteger(int) : GUIMessageCodes
-mServerCodes
«enumeration»
core::MServerMessageCodes
RegisterRequest
RegisterReply
LeaveRequest
LeaveReply
WBNRegisterRequest
WBNRegisterReply
DataRTSRequest
DataRTSReply
DataRequest
CommandRequest
CommandReply
WBNCommandRequest
WBNCommandReply
Error
Attributes
- id: int {readOnly}
- MServerMessageCodes(int)
+ fromInteger(int) : MServerMessageCodes
+ id() : int

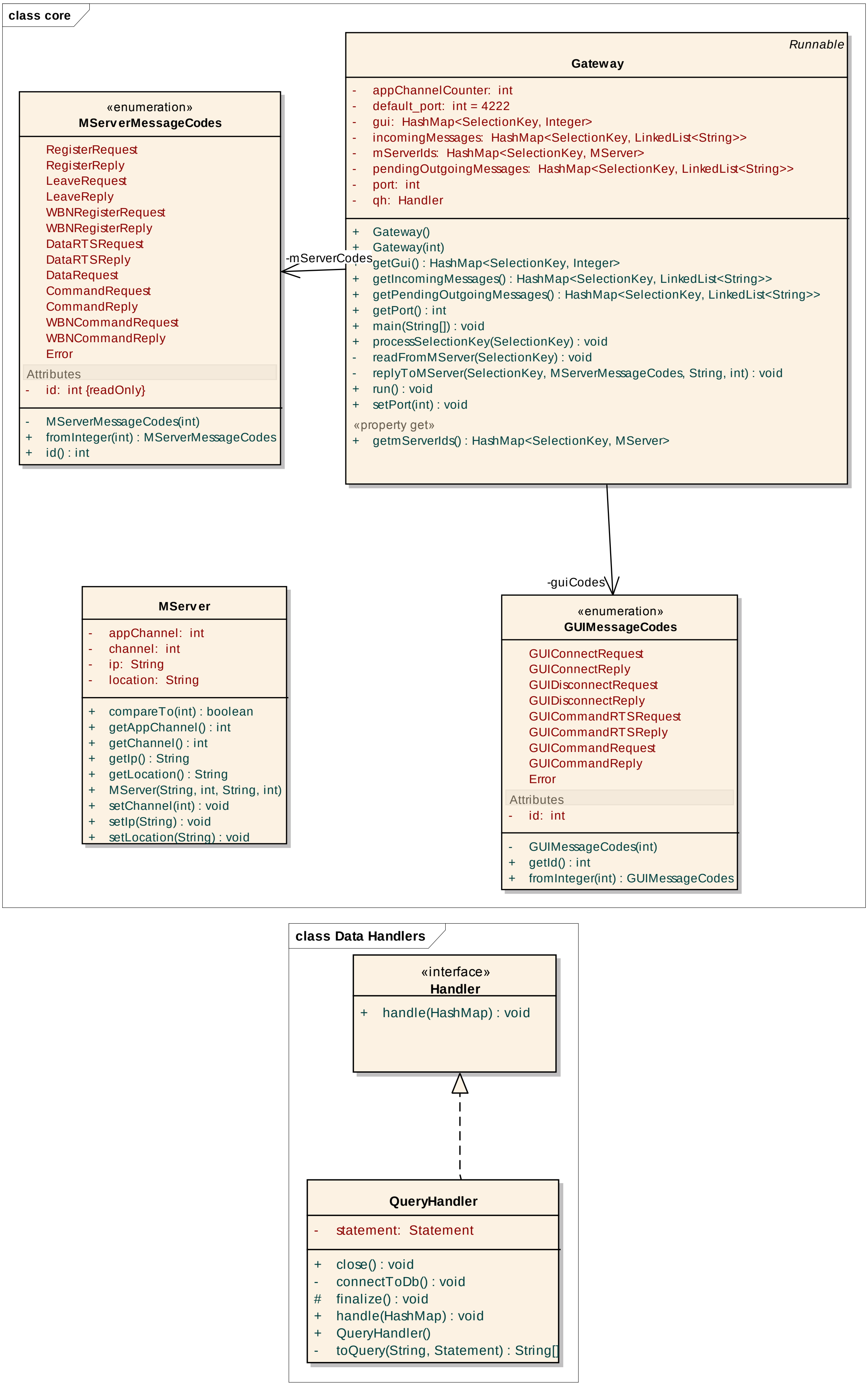


Figure 21: Preliminary class diagram for the Gateway component.

7.7. System requirements and performance measures

According to deliverable D2.3, the requirements towards the networking functionalities are to:

- Allow efficient sensing and control
- Ensure reliable operation for a long time, even with the use of limited power resource

Following the high level objectives, performance metrics have been defined as follows:

- Application performance: sensing accuracy, control performance
- Delay parameters: fusion delay, consensus time for distributed applications
- Network efficiency: the required network resources, energy consumption
- Network lifetime

Table 4 summarizes how the proposed solutions improve the target performance metrics, compared to the prior state of the art.

Table 4: Target performance metrics for network architecture and protocol design.

Protocol or function	Application	Delay	Network efficiency	Network lifetime
PHY layer functions	To monitor the PHY characteristics that dictate the network performance within tier 1, extract link quality models that reflect the propagation characteristics within the industrial environment and provide the related input to the above layers. Preliminary results (presented in D8.2) in the pilot plant indicate that, despite its small dimensions and the low data rate, the operation of a default WBN protocol stack is far from ideal in both the rural, as well as the industrial, environment. Additionally, by comparing these two types of environments, it becomes clear that the industrial operational space has no consideration for guaranteeing fair QoS conditions for all operational nodes, in spatio-temporal terms. Thus, as the distance of each source node from the sink increases, both the performance at the PHY layer, as well as the goodput, are severely affected. These results motivate the utilization of more sophisticated protocol stacks, which, as explained in D4.2, can address in a cross-layer manner the phenomena observed in the unfair conditions met in the industrial environment. The results of the complete study will be presented in Deliverable 4.3			
Adaptive threshold CSMA			To control energy consumption, minimizes a utility measure defined as the product of the packet reception rate and the throughput. Achieves three times the utility of the non-adaptive scheme.	

Cog-MAC		Can decrease end-to-end delay over multi-hop path, though the main objective is to decrease energy consumption.	By avoiding packet retransmissions due to Tier 2 interference, the energy consumption is decreased up to 30%, depending on the characteristics of the Tier 2 traffic.	
Load balancing RPL	Considers the acceptable delay of the control application as optimisation constraint.	The end-to-end delay may slightly decrease, but is kept within the predefined limits.		Achieves as balanced energy consumption as possible, given the delay limit, increasing the network lifetime.
Power efficient consensus	Maintains or decreases the consensus delay of in-network computation.		Decreases the overall energy consumption until consensus for most scenarios.	Decreases the energy consumption of Tier 1 nodes, increasing the network lifetime.

The small-scale field studies conducted so far in both a rural as well as the industrial environment, have provided useful insights for physical layer performance, which can be used as a guideline for the large scale deployment.

Table 5 provides the operational thresholds and accompanying parameters for point-to-point link performance for retaining the packet reception ratio in acceptable levels (> 85%) which can further be extended for a multi-hop topology.

Table 5: The empirical operational thresholds and accompanying PHY parameters for establishing point-to-point links with PRR ≥ 80%.

Operational Channels for the 802.15.4 2.4GHz band	Transmission Power Level	Inter-node distance (industrial / metallic environment)	Received Signal Strength	Link Quality Indicator	Additional Notes
All expect for channels 14,15	Above -7dBm	~ 8 m (with Line of Sight)	≥ -70dBm (for PRR ≥ 80%)	≥ 85 (for PRR ≥ 80%)	• Conventional Radio Duty Cycling (RDC) protocols will eventually result in severe clock drifts and TX-RX desyncronization. • When RDC is employed, ACK-bases schemes should be used with caution

7.8. Other relevant networking issues

The system architecture proposed by the project, does not cover all areas of network design and development. Specifically, for the following issues we suggest to use existing solutions.

Topology design is relevant issue for our scenario, since the placement of µservers is not determined by the sensing process, so it can be optimized to meet some objectives or the requirements that arise or are refined during the operation of the WBN. The issue of µserver placement has been investigated in the literature extensively. The results show that the location of µservers affects not only the network topology, but also numerous network performance metrics such as energy consumption, delay and throughput.

Based on *a priori* knowledge and the desired application requirements, designing algorithms for µserver placement should address the following three questions: how many µservers are needed, how to find their best location, and finally, how to assign Tier 1 nodes to the µServers. We propose that the last issue be dealt with the Routing protocols, while the first two issues should be considered jointly.

Placement of the many µservers can have different objectives to meet different application-specific requirements. The popular primary objectives include: load-balancing, fault-tolerance, long network lifetime or low energy consumption, decreased end-to-end delay. Based on the requirements of the HYDROBIONETS scenario, we suggest to optimize the µserver placement to achieve load balancing with constraints on the energy-consumption due to the multi-hop Tier-1 transmissions and on the end-to-end delay requirements of control and applications. Suitable algorithms from the literature are discussed in D4.1.

Synchronization is required to correct the clock-drifts of the nodes of the BioMEM network. A large variety of synchronization protocols are proposed in the literature that can be applied for our scenario.

Security is a very important issue for Cyber Physical systems, such as the BioMEM network. While the industrial areas are protected physically, it is possible to attack the wireless transmissions in the BioMEM network. The possibilities of incorporating network security in sensor networks are limited due to the limited storage, computation and processing capabilities. Nevertheless, known WSN protocols and operating systems have available security extensions (e.g. ContikiSec, compressed IPsec). The more complex problem of detecting attacks in the distributed environment from the received measurements is open research problem and needs to be addressed in the future.

7.9. In-network data processing

In-network data processing algorithms provide a set of tools for the control and actuation layer, such that both control strategy and actuation decisions can be performed in a distributed fashion. In this way, convergence of control processes and tracking capabilities of estimation algorithms strongly depend on the deviation that these in-network processing algorithms introduce with respect to a centralized strategy. Therefore, the goal of these algorithms is to reduce the error to an extent such that upper layer requirements are fulfilled. In case of a deterministic environment, the least square error (LSE) represents the cost function to be minimized. On the other hand, the minimum mean square error (MMSE) is used for stochastic objectives, characterizing the average performance and variance behaviour over multiples realizations.

Additionally, since most of the in-network processing algorithms are iterative processes, the convergence time, defined as the number of iterations required by the algorithms to reduce the error by a specific factor is also considered. This issue is closely related to the instantaneous topologies that arise at each iteration of the process. Obviously, a fully connected topology minimizes this time.

However, together with the path loss exponent and the required signal-to-interference-plus-noise ratio, the number of active links at each instantaneous topology clearly impacts on the consumed power at this iteration. This leads us to another important parameter that defines the performance of the system: the required energy to carry out the in-network processing algorithm, that is, the consumed power per time unit.

Finally, due to the collaborative nature of these algorithms, it becomes crucial to the lifetime of the network, defined as the total time that the network is able to correctly perform the algorithms before a certain number of nodes run out of batteries.

7.10. Control and Actuation

In our BioMEM network architecture and protocol stack, the sensors, controllers and actuators co-exist in a spatially distributed manner where the interconnection of these components is achieved and ultimately relies on a communication network that uses the IEEE 802.15.4 protocol. In our system scenario, we have four fundamental units: the sensors that sense the state of the process, the communication protocols, the controller, and the actuators. The process state includes concentration of substrate, active biomass, inert biomass, biofilm thickness, biofouling potential, and chlorine concentration. Measured values of the process state are used in a closed control loop by calculating the control outputs to drive the actuators. The control strategy is based on a linear quadratic feedback law. The design of the optimal control strategy must cope with the communication protocols present in the network, which connect the sensors attached to the plant to the controller. In our scenario, we have studied the delay induced by the protocol on the transmission of packets. The nature of the delay can be deterministic when we use a beaconed enabled IEEE 802.15.4, or random when we use a beaconless IEEE 802.15.4 which has a random access scheme. An important factor we have considered is the sampling interval of the process state. We have shown that this is a factor that should be balanced with regards to the data rate that is supported by IEEE 802.15.4. Sampling more frequently will give more information to the controller, but also will generate more traffic, which might not be handled by the protocol.

In addition to delays and jitters in packets, there are cases where packets do not reach the controller at all. There have been many studies to ensure the closed loop control stability in the presence of packet losses. We have considered a simple control strategy that is able to cope with packet losses and the delay introduced by the network, provided that the MAC parameters are adapted. This has resulted in a control strategy that is based on quantization of the state of the process, self-triggered control, and adaptation of the MAC parameters in a decentralized manner. Finally, once the control decision is available, it is actuated via the standard actuators available at the plant.

The HYDROBIONETS system is connected to the current system through an OPC client written in JAVA code. The OPC client uses the libraries for Utgard, which provides functions that enable the connection to an OPC server. When the HYDROBIONETS system starts working, it initializes the OPC client to connect the OPC server of the current system, by using the information such as the host address of the OPC server, the Class Id of the server. If the connection fails, a warning message will show in the terminal and try for reconnection later. Once the connection is done, the OPC client polls data from the OPC server periodically.

Based on these data from the OPC server and the sensor readings from the HYDROBIONETS system, the controller determines the control strategy and makes the control decision. The decisions, together with alarms if necessary, are sent back to the OPC server through the OPC client so that the decision is actuated by the actuators at the plant.

Table 6 describes the deliverables of each task where more detailed information can be found.

Table 6: Deliverables where more detailed information can be found.

Design issue	**Deliverable**
Network architecture	D2.3, D4.1
Topology control, µserver placement	D4.1
Protocol architecture	D4.2
MAC, Routing	D4.2
Network Management	D4.2

8. Data management and visualization

The Data Management and Visualization (DMV) module is implemented as a part of the Application Layer at the Gateway. This module consists of a set of individual components, which interact with each other, and is responsible for performing the following tasks: i) uncertainty quantification; ii) online estimation of pairwise correlations between the recorded data streams; iii) uncertainty-aware detection of extreme events; iv) bidirectional communication with the sensor network and nodes reprogramming; and v) visualization of the available information. The interactions between the distinct components of the DMV module are shown in in a layer-based structure, where upper layers exploit the information generated by the lower ones.

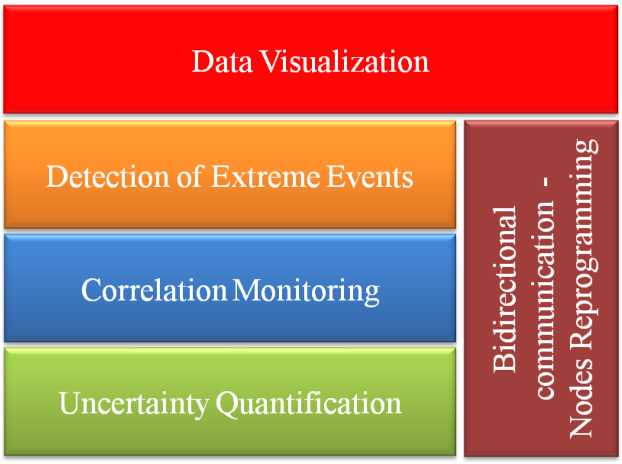


Figure 22: Data management and visualization module.

8.1. Uncertainty quantification

The uncertainty quantification component receives raw sensor data streams as input and computes the underlying uncertainty. Two options are provided for the quantification of uncertainty, namely: a) by using spreadsheet tables to list, quantify, and combine the individual sources of uncertainty; and b) by following a model-based approach, where a prior probability distribution is fitted on the raw data. Depending on the specific application requirements, a system operator has the flexibility of reusing or not the output of this component, that is, the estimated uncertainty for a given data stream, as the entry of the other components of the DMV (e.g. extreme event detector). To this end, this component can be selected independently by the system operator, such that quantification and reporting of the underlying uncertainty is performed, while uncertainty-aware detection of extreme events is not selected. However, we emphasize that the estimation of uncertainty can be still performed continuously in the background (see D7.2 for more details).

8.2. Online estimation of pairwise correlations

This component extracts subsets of sensors whose data streams are highly correlated (that is, with a correlation above a user-defined threshold). This is done in a fast online fashion for all the pairs of sensors in the initial full set. The algorithm proceeds by processing the data in overlapping windows with the window size and the step size being set by the system operator (a detailed description of the method can be found in D7.3). The purpose of this component is to guarantee the validity of the subsequent detection of possible extreme events. Similar to the uncertainty quantification module, the correlation monitoring module can be selected individually by a system operator. In particular, correlation monitoring can be performed independently of the extreme events detection, by reporting simply the subsets of highly correlated sensors. In addition, the selection of this module is also independent of the activation of the uncertainty quantification module. Thus, in the case that an estimate of the underlying uncertainty is not available (uncertainty quantification module is deactivated), then correlation monitoring is based on the acquired raw sensor data.

Synchronization: In order to ensure the correlation monitoring is valid, synchronization between the distinct data streams is applied. This is carried out by employing the time stamps of the transmitted packets.

8.3. Uncertainty-aware detection of extreme events

This component is dedicated to providing alerting notifications for abnormal behaviour either of the monitored variables or the sensor devices. In particular, three methods for the detection of extreme events were modified in order to account for the underlying data uncertainty. The available options are the following: a) compliance with operating limits; b) method of block maxima; and c) method of peaks over a threshold. Each method has its own specific inputs (see D7.2), while all of them report whether an extreme event occurs in the current windows of the monitored sensor data streams. In order to remain compliant with the standard implementation of these methods, the system operator has the flexibility to de-activate the use of the estimated uncertainty as an additional input.

8.4. Bidirectional communication – Node reprogramming

In order to support extra control of the HYDROBIONETS infrastructure, bi-directional communication with the wireless sensors is supported. The following main options are provided:

- *Start* / *Stop*: start and stop the data collection
- *Sample*: sample a measured value from a sensor (in query driven mode)
- *Change sensor parameters*: two types of parameters are considered: a) frequency of data sampling (for continuous communication mode); and b) operational thresholds (for the sensors working in an event driven manner)
- *Reprogram*: in case there is the need to change the node operation (fix software bugs, change the node protocols of communications, etc.)

Focusing on the last option, a robust and efficient web service is designed, which enables the wireless reprogramming of the BioMEM network nodes. This service is based on a cross-layer reprogramming protocol, where the MAC decisions are taken to favour the node reprogramming. Moreover, the proposed service makes the process accessible from any authorized computer and transparent to the user, hiding the dissemination protocol details (see D7.3).

8.5. Data visualization

The data visualization component enables the flexible and scalable visualization of all the available information within the HYDROBIONETS infrastructure in a dynamic, real-time fashion. More specifically, it provides two major functionalities, namely: a) visualization of the recorded raw sensor data in the current time-window, along with a basic compact summarization (e.g. maximum & minimum values, average, and standard deviation); and b) visualization of the network condition (e.g. routing, connectivity, and packet loss). The implementation of the data visualization component is based on a flexible, scalable and secure structural design exploiting multiple tools. For instance, PHP is used in the back-end to support the communication with HYDROBIONETS Database, while HTML, CSS, and JavaScript are used in the front-end. Moreover, its widget-oriented design simplifies straightforward extensions for future upgrades, while automatic customization for use with tablets and smartphones is also enabled.

9. Recommendations for HYDROBIONETS system improvement

9.1. Sensor platform

- Connection to the mains instead of battery powered.
- Try to avoid the screws to waterproof the sensor cell. A magnetic strategy should be considered.
- Increase the robustness of the chip holder.
- Indicators/alarms to be included in the sensor platform.
- Level indicator of KCl bottle.
- Conductivity meter to ensure seawater flushing before measurement.
- Battery level indicator.
- External LEDs: OK, error, sensor error, alarm, etc.

9.2. Communication

- On-node and in-network link quality prediction and estimation of packet losses distribution for alleviating from burst packet losses.
- Energy-oriented metrics in routing decisions.
- Integration the platform with the remote reprogramming modules.

9.3. Visualization tool

- Efficient simultaneous visualization of multiple (possibly of distinct type) sensors in the same plot.
- Option to switch between constant frequency and adaptive sampling for a selected set of sensors.
- Add more alerters (e.g. KCl level, valve condition), which will be identified indirectly via the acquired sensor measurements.
- Increase interaction capabilities between a system operator and the visualization GUI by supporting compatibility with touch screens.

9.4. Control

- Increase the robustness of control algorithm against low sampling frequency.
- Enhance the control algorithm so as to be self-adaptive, i.e. to automatically modify its operation parameters according to acquired measurements and environmental conditions.
- Introduce prediction schemes in the control algorithm, e.g. model predictive control.

Appendix A – *Operating Manual*

This Appendix is confidential and so is not included in this version of the document.