EMMON WHITE PAPER

TOOLSET AND LESSONS LEARNED FROM LARGE SCALE DEPLOYMENT EMMON

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1. EMMON Project Overview

The EMMON project [RD-1] is an European Research and Development (R&D) project, sponsored by the 7th Framework Programme (7FP), ARTEMIS Joint Undertaking (JU) initiative and integrated in the Industrial Priority "Seamless connectivity and middleware".

EMMON motivation originated from the increasing societal interest and vision for smart locations and ambient intelligent environments (smart cities, smart homes, smart public spaces, smart forests, etc.). The development of embedded technology allowing for smart environments creation and scalable digital services that increase human quality of life.

The project goal is to perform advanced technological research on large scale distributed Wireless Sensor Networks (WSN), including research and technology development activities in order to achieve the following specific objectives [RD-2]:

- Research, development and testing of a functional prototype for large scale and dense WSN deployments;
- Instantiate the EMMON WSN system architecture in a real-world application of several hundred nodes (at least 400);
- Advance the number of devices by one order of magnitude (10 thousand nodes or above);
- Improve reliability, security and fault tolerance mechanisms in WSN;
- Identify and capture end-user needs and requirements, as well as operational constraints;
- Determine a path for exploitation of project results;

EMMON's main objective is the development of an integrated framework of technologies to enable large-scale and dense real-time monitoring of specific natural scenarios (related to urban quality of life, forest environment, civil protection, etc.) using Wireless Sensor Network (WSN) devices in a reliable, robust and scalable way.

Areas of application for the project include a multitude of physical environments where continuous, large scale monitoring and situation analysis are of great interest, such as hydrographical systems (rivers and dam's), urban areas quality of life monitoring (pollution and noise), regional climate/marine monitoring, civil protection (forest fires, pollution propagation, etc.), natural resource monitoring, energy production prediction, industrial plant monitoring, personal health monitoring and precision agriculture, just to name a few.

The increased environment awareness and detection of abnormal variations, allied with the possibility to rapidly broadcast alarms and alerts, improves human quality of life and sustainability.

As a result of the objectives described above, the main project results include:

- Medium scale deployment of a fully-functional system prototype in a real world scenario (composed by hundreds of nodes);
- New WSN embedded middleware with better overall energy efficiency, security and fault-tolerance;
- New efficient and low power consumption WSN multilevel communication protocols and reliable middleware for large scale monitoring;
- Simulation models for WSN behaviour analysis;

- Centralized C&C Centre for easy and centralized monitoring;
- Mobile C&C station or device for local access, diagnosing, viewing and troubleshooting of the network;
- Comprehensive Toolset for assisting network planning and deployment of large scale WSN systems.

1.1 EMMON architecture

The EMMON project architecture is composed of several tiers, as can be seen in Figure 1.

Tier 0 is composed of the sensing elements of the network; this is where the actual sensing is performed. Above this layer is Tier 1 which is composed of Cluster Heads that are responsible for the communication and aggregation of the information. Tier 2 contains the gateways which serve as the last aggregation point and at the same time as the interface from the IEEE802.15.4 domain into the IP domain.

Above Tier 2 all other Tiers - N and M in Figure 1, are IP based networks without the limitation in bandwidth of the WSN.

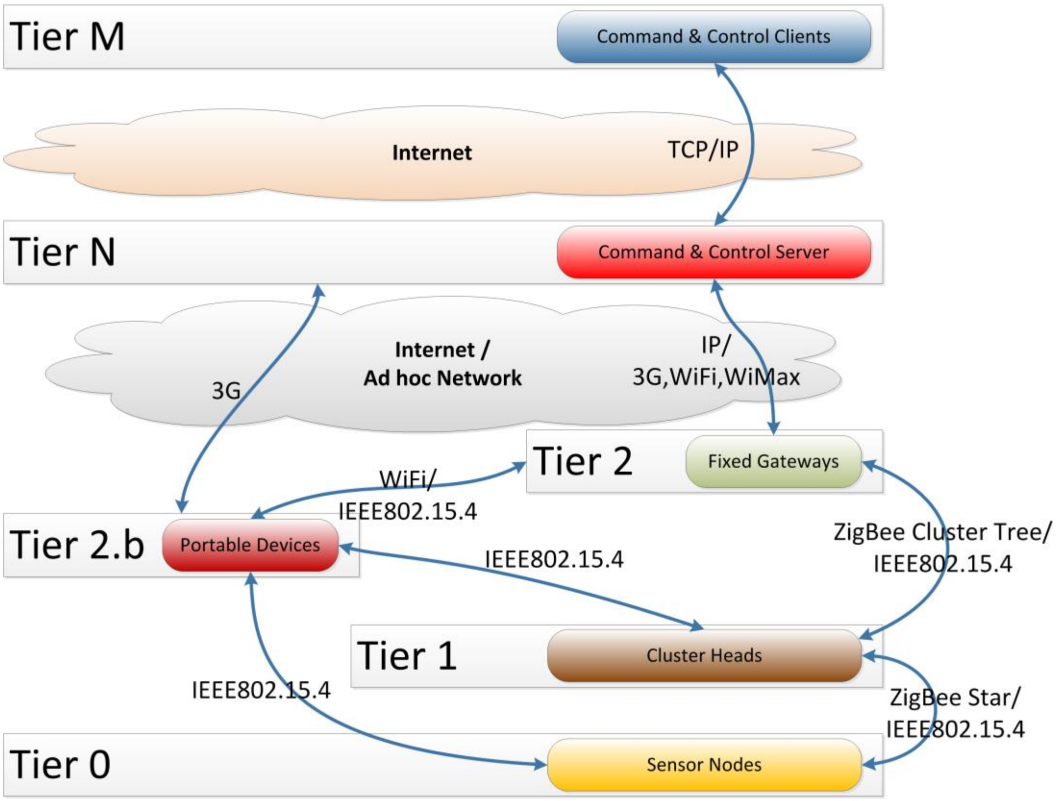

Figure 1: EMMON architecture

2. Deployment scenario

The Urban Quality of Life scenario was identified as the best to validate the EMMON architecture in real-life situations. This scenario consists on the monitoring of temperature, relative humidity and light, in order to understand how and where it is possible to reduce electricity consumption due to lighting and air conditioning.

The tests were performed at SANJOTEC [RD-3], the Business and Technology Centre of S. João da Madeira, Portugal. Their facilities are composed of a single building with four floors with offices and rooms. The ground floor was used for the testing activities. Since this is an indoor scenario, several additional and specific requirements had to be taken into consideration.

Sensor readings regarding temperature, light and relative humidity were collected during these testing activities, directly from the on-board sensors present in the TelosB motes. The accuracy of the readings was not considered relevant for this testing scenario as the Network Architecture (including the EMMON communication protocol and the Middleware) was the main focus of this testing scenario.

The testing activities were split in two phases. Since the range of the transceivers and the distances between nodes have a significant impact on the choice of network topology, the first phase consisted in creating a radio connectivity map. The second phase targeted the test of a representative EMMON network (DEMMON1).

For Phase 1, a series of motes based on EMMON Cluster Heads (CH) were installed along one corridor and the main hall. These motes were associated with each other, in a single branch tree. The main goal of this tree was to produce packets at a constant energy level, thus populating the environment with radio signals. This allowed the deployment of sniffers in specific points to understand the quality of the received signals, at a specific point relative to all the CH. At the end this allowed for the definition of the EMMON network structure for Phase 2.

In Phase 2, the goal was to have a complete EMMON system deployed at SANJOTEC. A network with 27 nodes was therefore deployed at their facilities. CH's were placed in the ceiling, in the positions defined during Phase 1, and the Sensor Nodes were placed on the walls (around 1.5m to 2.5m above the ground). The Gateway (GW) was placed in an office accessible through the corridor (with restricted access). The GW prototype is composed of a laptop with a TelosB attached to it.

A set of tools were used to verify the test results (pass/fail criteria). The C&C Client was the main tool, but other – and passive – tools were used. These other tools only recorded what was going on in the system, without interfering with it.

In Phase 3, a large-scale network was deployed in SANJOTEC, composed of 412 motes, 6 gateways and 1 C&C server (see below).

3. Project Developments and Results

3.1 Overall Project Results

For the EMMON Project the overall Quantified goal from the Technical Annex was "The quantified goal of the project is to create an integrated framework for large scale and dense wireless sensor networks that allow effective monitoring for more than 10,000 devices." The main aim was to "Solve the scalability problem of WSN".

To help focus the work this was then split into 6 specific goals to help direct the project towards this objective. These were as follows:

1. Research, develop and test a functional prototype for large scale and dense WSN deployments in a test bed environment.

2. Instantiate the EMMON WSN system architecture in a real-world application of several hundred nodes (at least 400).

3. Advance the number of devices by one order of magnitude (10K or above). Prove scalability by:

    a. Extensive experimental performance analysis in an integrated test bed and real world application;

    b. simulation results for 10K nodes;

4. Improve reliability and fault tolerance mechanisms in WSN

5. Identify end-user needs and requirements, as well as operational constraints

6. Determine a path for exploitation of project results

EMMON considers that each of these specific goals were achieved and the evidence of the successful completion of these was presented to the Project Officer at the final Project Review.

To allow the project to display the success of the above objectives the final review was held at SANJOTEC premises, in São João da Madeira, Portugal (www.sanjotec.com). In these premises the EMMON project team had set up a full working demonstrator (codenamed DEMMON2). It occupied three floors, not all the areas were covered due to privacy issues but most of the floors were covered. It was composed of 412 motes, 6 gateways and 1 C&C server. The six gateways were connected to the C&C using a private IP-based network setup for the project in the garage and using SANJOTEC's private IP-based network on the two other floors.

The demonstrator objective is to show the innovative aspects of the global EMMON network architecture. The C&C moved from a traditional measurement station based user interface into an interface based on abstract user-defined monitoring objects composed of a group of sensors. In this version, these objects are automatically built based on motes' positioning. The user defines the area of the object and the system will compute the monitoring data from the set of sensors. This geographical abstraction is used across all layers of the network to simplify reasoning and save processing and storage: it is used at the middleware level to enable in-network aggregation and at the routing level for geographical queries disseminations. The demonstrator also validated the system in a real end-user environment and was used to obtain experimental data to validate scalability data obtained from simulation and emulation.

For DEMMON2 this scalability was shown and proven through using over 400 nodes within the SANJOTEC facility. The scalability was also shown through Simulation results. The project performed simulations at all layers of the system architecture:

- Network level (up to 501 nodes per Patch)
- Middleware level (up 11659 nodes)
- Gateway <-> CC level (up 144 Patches)

Adding to this, the project also used Emulation, with real middleware code to emulate the behaviour of thousands of nodes and this showcased results for up to 2600 nodes.

3.2 Overall Project Developments

Several relevant works on WSN architectures and solutions supported by working prototypes have been proposed in the literature and in the scope of research projects, as evidenced in Section 3.2.1. However, to the best of our knowledge, none of them fulfils all requirements for large–scale and dense real–time monitoring [RD-7]. In this context, we believe that the EMMON system architecture outlined in this white paper pushes the state-of-the-art by combining the following aspects:

- it encompasses all system components, from a Command and Control (C&C) graphical user interface to hardware (based on COTS platforms);
- it considers several QoS properties simultaneously, namely scalability, timeliness (including real–time support), energy–efficiency, security and reliability/robustness;
- it builds upon specific user/application requirements [RD-6], e.g., in terms of sensors number/granularity, sampling frequency and end-to-end delay, and also a thorough analysis of problems to address and of previous work ([RD-7]), ranking possible solutions/technologies according to a weighted set of criteria;
- it is based on the most widely-used standard and COTS technologies for WSNs - IEEE 802.15.4 [RD-14] and ZigBee [RD-15]; this brings obvious benefits for system designers and increases the confidence of the end-users, reducing time to market;
- it augments IEEE 802.15.4 and ZigBee with important add–ons, such as traffic differentiation [RD-16], time–division cluster scheduling [RD-17], dynamically adaptable duty-cycling, mitigation of the hidden–node problem [RD-18] and downstream geographical routing [RD-2];
- the baseline IEEE 802.15.4 and ZigBee protocol stack is supported by a solid critical mass, designed and implemented in synergy with the TinyOS 15.4 [RD-19] and ZigBee [RD-20] Working Groups and backed up by expertise from the authors [RD-21];
- the WSN architecture is supported by a unique and complete planning, dimensioning, simulation and analysis toolset, namely for system planning (deployment, worst-case dimensioning), protocol simulation, remote programming and network sniffing ([RD-4];
- it provides a reliable middleware for use in resource-constrained devices, and enabled (to the best of our knowledge) the largest middleware-based WSN deployment to date;

- the baseline architecture has been tested and validated by extensive simulation and experimental evaluation, including through a 400+ node test-bed, which is, to the best of our knowledge, the largest single-site WSN test-bed in Europe to date.

3.2.1 Outline of Some Relevant Previous Work

Despite the plethora of solutions presented so far in literature [RD-7] encompassing all aspects of WSN–based systems ranging from networking protocols to application algorithms, it is important to look at the results of real–world deployments [RD-8]–[RD-13] in order to infer best practices that can be re–used in EMMON and see how these solutions can be glued together in a whole working system.

Aiming to cover a 10km by 1km perimeter with 10k nodes, project ExScal [RD-8] fielded a 1000+ node WSN with a 200+ node acting as an ad hoc backbone network of 802.11 devices in a 1.3km by 300m remote area in Florida during December 2004. The application targeted by ExScal was the detection and classification of multiple intruder types over an extended perimeter. This project organized the biggest deployment to-date and its multitiers network architecture is therefore very relevant to EMMON. Nevertheless, the application targeted is quite different and a planned and regular topology makes the solutions adopted too specific. Finally, almost no information about the communication protocol used is available.

VigilNet [RD-9] was one of the major efforts in the community to build an integrated WSN system for surveillance missions. Its goal was to develop an operational self–organized wireless network to provide tripwire–based surveillance with a sentry–based power management scheme, in order to achieve minimum 3–6 months lifetime with current hardware capability. The system should also support timely detection, tracking and coarse granular classification of vehicle and personnel targets over all kinds of terrain. The main deployment scenario is actually along a road for detecting vehicular passing. The application scenario of VigilNet is not related to EMMON, but the energy–aware design methodology for large scale networks used is of potential interest.

Motivated by the observation that future large-scale sensor network deployments will be tiered, consisting of motes in the lower tier and masters, relatively unconstrained platform nodes, in the upper tier, the Tenet [RD-10] architecture pushes application development simplification and software reuse. This is achieved by constraining multinode fusion to the master tier while allowing motes to process locally–generated sensor data. EMMON adopts a similar approach is similar and builds from some of the Tenet design principles. The Tenet system, however, does not currently support delay–sensitive applications, while our EMMON architecture includes functionalities to specifically address several QoS properties. Indeed, some of the design principles (only 2 tiers, no aggregation at the lowest tier) hinder scalability.

e–SENSE [RD-11] provides heterogeneous wireless sensor network solutions to enable Context Capture for Ambient Intelligence, in particular for mobile and wireless systems beyond 3G; thus enabling multi–sensory and personal mobile applications and services, as well as assisting mobile communications through sensor information. Three classes of applications were investigated: (a) body sensor network applications, (b) wireless sensor network systems deployed in environmental or object sensor network applications requiring localization and positioning and thus having some form of geographic notion, and (c) wireless sensor network systems deployed in environmental or object sensor network applications not requiring explicit localization support (such as converge–cast applications). The network architecture comprises various possible instantiations of mesh WSNs that are connected via gateways to a core network. The core network can be a beyond 3G mobile communications system or a conventional wired backbone network. This project presents three different instantiations but does not provide a fully-implemented unified architecture and does not address scalability.

The WASP project [RD-12] aims to develop a generic and portable application development model built from a variety of the existing communication and security protocols and operating systems. Service–oriented architecture is proposed to integrate while networks with the Internet cloud architecture. As such, the work does not aim to develop novel algorithms or protocols or to solve a particular technical task. Instead, the authors evaluate a vast range of existing WSN networking protocols in order to identify their characteristics and commonalities, as well as their potential for cross-layer optimization. Two protocol stacks are proposed for use in the project's two main application scenarios: herd control and elderly care. The project investigates a range of the existing WSN programming models and proposes an enterprise integration architecture with the goal of developing a general application programming model. The overall goal of the project is to make WSNs usable at the industrial level, i.e., to shorten the gap between the academic research (variety of protocols and tools) and industrial applications (i.e., tools and methods that are used for commercial applications). In practice, many of the project's design choices were made with mainly the herd control application scenario in mind thus making direct transfer of the project's results difficult. The project's documentation, however, offers many valuable insights as to the characteristics of the existing WSN hardware and software and it proved useful for the choice of EMMON's networking and hardware components.

RACNet [RD-13], presents a practical example of how large scale embedded systems for monitoring application can produce huge energy and cost savings. In particular, by considering that in the field of large data centers it was estimated that only 30% to 60% of the total consumed energy is related to the IT equipment, it is evident how minimizing the losses in power delivery and conversion processes or in environmental control systems such as Computer Room Air Conditioning (CRAC) units, water chillers, and (de)humidifiers is of paramount importance. The most interesting aspect of RACNet is that it proposes a solution to maintain robust data collection trees rooted at the network's gateways. The mechanism's distributed nature allows nodes to independently react to topology changes including degraded link qualities and node failures. As EMMON, it builds upon the IEEE802.15.4 protocol and includes an analysis of the co–existence with other technologies, such as WiFi, which share the same band. Moreover, RACNet assumes a network topology composed by multiple trees each of them routed at the GW and working on different radio channels to minimize the mutual interference. In EMMON we opted for a similar approach, but instead of implementing a token–based communication among the nodes where only the node with the token can transmit its measurements to the GW at a given time, we allow for a more structured network coordination among clusters of nodes focusing on guaranteeing a given level of QoS. Moreover, in this application it is assumed that every nodes have an external power supply, so that energy is not an issue. In EMMON, the distributed coordination among clusters allows for energy savings of the nodes batteries. We think that this is a further improvement to achieve lesser energy consumptions or to increment the spatial resolution of the measurements by deploying additional battery powered nodes.

3.2.2 Design Guidelines

A more exhaustive and extensive analysis of technologies and projects has been done in [RD-7]. In order to infer the best practices to be applied to the EMMON architecture design, this section summarizes the lessons learned from other projects that we found the most useful.

1. Keep it simple: simple solutions are easier to handle and debug. Moreover, interacting with the end-user will help identifying the appropriate requirements, hence allowing a reduction on the number of features and the solution's complexity.

For example, it can be useless to design a complex congestion control algorithm if the probability of congestion is negligible. However, it is worthwhile to note that “simple” doesn’t mean “trivial”. Finding the simplest solution to achieve a given goal might be a complex task!

2. Modular design: it is of paramount importance to proceed by steps using a modular design approach. In the first phase, it is important to include only the most basic features in the design cycle and evaluate their correctness by both simulation and testbed testing. In subsequent steps, more functionality can be added and validated by iterating design cycles and assessments.

3. Embed tests in the design cycles: using a testbed is important and tests have to be included in the design refinement cycles (test-it-fix-it), because many properties and problems appear only in real world deployments. Therefore, it is important to have the possibility to run the test-bed in an environment that reproduces similar conditions as the real deployment as well as using consistent simulation models.

4. Interoperability matters: i.e. the best MAC protocol may not fit the requirements of the best routing protocol, thus it is important to assess the interoperability between technologies to evaluate the adequateness of each of them.

5. Technical maturity: it is important to choose technologies that are mature enough, especially those that have been implemented, preferably having been extensively used and tested by many people.

6. Availability of expertise: gluing components together takes a lot of effort and requires in-depth knowledge of individual components. It is therefore important to choose technologies for which knowledge is available in the design team.

7. QoS provision: to achieve predictable resource guarantees (e.g., bandwidth and buffer size) all over the WSN, it is mandatory to rely on structured logical topologies such as cluster-tree with deterministic routing and MAC (Medium Access Control) protocols. Basically, these network models rely on (i) the use of contention–free MAC protocols (e.g. Time Division Multiple Access (TDMA) or token passing) to ensure collision–free and predictable access to the medium, and (ii) the ability to perform end–to–end resource reservation. These represent important advantages of structured and deterministic topologies when compared to what can be achieved in flat mesh–like topologies, where contention-based MAC protocols and probabilistic routing protocols are commonly used.

4. Limitations and problems

From the phase 2 deployment described in section 2 the following limitations and problems were found:

- **Positioning**: as the aggregation of sensor readings might need to be associated to the rooms to which the nodes belong to and not just their geographical location, this poses a challenge. This might be tricky if we consider that sensors could be placed on both sides of a thin wall, thus in different rooms but very close geographically.
- **Monitoring Objects**: the current EMMON Middleware only allows rectangle monitoring objects aligned with North-South and East-West Axes. This very rarely happens with real buildings;
- **Reported Measured Area**: the C&C Client doesn't support the reported measurement area. This area can, and most certain always will, be different from the queried area. Also, if part of the network loses connection with impact on the queried sensors, this is not presented to the user. Related to this, the EMMON Middleware (MW) might produce more than one report in a single measurement. This will adapt the queried area into some measured areas according to the gaps existing in the SNs distribution. The C&C Client shall support this single-query/multiple-reports functionality;
- **Time Aggregation at the Sensor Nodes**: this proved to be unreliable. In a test with 540 values collected per report period, the values reported were completely different from the values being returned by similar queries running at the same time with the same sensor but reporting more often;
- **Power Consumption**: there are yet no figures on power consumption for a TelosB running EMMON. This will need to be further analysed, to determine the power consumption of an EMMON TelosB mote in several configurations (role, sending beacon, reading sensor, processing aggregation, etc.). This will also allow estimating the lifetime of the nodes. This power monitoring needs to be developed and will use the board's integrated capability to measure the main circuit voltage in order to alert when it is reaching the limit;
- **Prototype Maturity**: the tested implementation is a prototype. It was the first full integrated system prototype. It was expected that the immaturity of the system would incapacitate the operational tests and that the results of the tests might be less than great. Surprisingly, the system showed some good overall behaviour. It was possible to monitor SANJOTEC facilities remotely and proceed with operational testing.

The identification of these limitations is important not only to help in reaching a commercial-line product, but also to reach a baseline system mature enough to support the validation of new implementations of new functionalities and improved modules.

This baseline system will be the framework for testing specific implementations of new functionalities, new methods, and even new EMMON modules. For that it shall contain functionalities to support the system management such as over-the-air programming, over-the air configuration and over-the-air reset.

These limitations were improved and corrected before the final EMMON demonstrator (phase 3) DEMMON2. This phase 2 deployment was a very important smoke test performed to the EMMON system.

5. Lessons Learned and Improvement Suggestions

The project had the chance to setup the EMMON system in a live real environment. This deployment allowed the team to validate the EMMON architecture and system implementation. A number of lessons were also learnt from dealing with a large-scale deployment in a live site. Mote Deployment

The solution presented ([RD-5]) for mote fixing was used with success in floor 0 and floor -1. The Tesa Power Strip performed as expected and using the proper handling cares it worked without problems.

The deployment is an error prone and time consuming process; this should be made more agile in future improvements made to the system. Investigations should be made in direction of having a layout which is less rigid but that could maintain some of the structure imposed by the layout. It was noticed during the deployment that it was sometimes a hard task to deploy the defined layout. This was caused by minor mistakes like: programming the incorrect node or placing the node incorrectly; and were in some occasions hard to identify.

5.1 Mote Configuration

Most of the mote configuration like parent information, network depth level and identifier are configured offline. This is error prone and can sometimes lead to some of the problems described in the previous section.

A solution for this was devised to include in the first step of the boot process of the motes a step in which these would wait for a configuration message. Since this was linked to the OTAP development it was never implemented because of the higher priority tasks.

Nonetheless this is an interesting feature to be included in the future.

5.2 Labour intensive tasks

During deployment, there were several tasks which seemed at first glance very small and easy caused some disturbance in the process of deployment. One good example of these tasks was the preparation of the enclosures. The procedure was very simple: drill holes for light sensor and attach a sticker with the sponsors.

This seemed like a smaller task that could be performed easily and quickly. And although the each item was prepared fairly quick, the big number of enclosures to prepare made the whole process last some time. These tasks should always be taken into account and estimated properly to avoid delays.

5.3 Time synchronization

Although the values received were an improvement upon previous test results some problems were detected in this test phase. In this test there was no detection of the clocks overflowing but within some motes an uneven clock running was detected.

To allow the tests to be passed an interim solution was implemented. For the future though an upgrade is required to produce a more evolved solution. Overall, while time synchronisation in WSNs is not a significant research challenge, designing a practical implementation that is suitable for very large-scale networks with only minimum message, memory and processing overhead is challenging.

5.4 Positioning

The aggregation of sensor readings into meaningful information to the user might not depend directly on the geographical coordinates of the motes. As an example we might have a room with several motes at two different heights, for the purpose of this example let us call them high and low, and we might aggregate all the highs of that room and all the lows; this will provide two different monitoring objects with disjoint group of sensors in the same geographical area. DEMMON2 version only supports 2 dimension coordinates.

The aggregation of sensor readings will, in the majority of the cases, match physical objects. At SANJOTEC scenario it will match the room's walls. This means that to select a room as a monitoring object, the creation of the object must be very precise to really select the correct sensors. To illustrate this, imagine two rooms, room A and room B, separated by a relatively thin wall with sensors in both sides of the wall, room A side and room B side.

A complementary approach to geographical routing would be location ID that would be programmed in the sensors depending not only on their physical position, but also depending on other characteristics that might define a group of sensors (e.g. inside room A). This would allow to complement the geographical information so that SNs that are inside the geographical area but do not belong to the group are not considered in the query. In our example, we could define an area that completely overlaps room A, including therefore Sensor Node (SN) at room B wall, but also including the ID assigned to room A. This way SNs outside room A would disregard the query.

5.5 Monitoring objects

The current implementation of the EMMON MW allows only for rectangle monitoring objects aligned with North-South and East-West axis. Very rarely will a building completely aligned with these axes and contain only rectangular rooms. Furthermore, the scenarios might not consider rooms, but areas that can be made of rooms, corridors and halls.

5.6 Reported Measured Area at C&C Client

The C&C Client in this implementation version does not support the reported measurement area (even though it is reported by the middleware). This area can, and most certain always will, be different from the queried area. Furthermore, if part of the network loses connection with impact on the queried sensors, then it would be good to present that to the user. This way, not only would the user explicitly see a change in the areas, but would also understand that the value seen no longer represents the original area, but a smaller one.

Also, related to this, the EMMON MW might produce more than one report in a single measurement. This is due to the aggregation parameter that would control how distant the sensors are to be considered for aggregation. This will adapt the queried area into some measured areas according to the gaps existing in the SNs distribution. The C&C Client shall support this single-query/multiple-reports functionality.

5.7 Power consumption

Currently we don't have the figures on power consumption of a TelosB running EMMON. We must execute some laboratory tests with an Ampere-meter to evaluate the power consumption of an EMMON TelosB mote in several configurations (role, sending beacon, reading sensor, processing aggregation, etc.). This will provide the figures to calculate the power consumption of any EMMON node implementation and estimate the lifetime of the batteries.

We can also validate the figures in a real EMMON network. To do so a small network can be deployed at partner facilities with power monitoring. This power monitoring needs to be developed and will use the board's integrated capability to measure the main circuit voltage in order to alert when it is reaching the edge.

5.8 Prototype Maturity

The EMMON implementation tested in these testing procedures is a prototype. It was the first full integrated system prototype. It was expected that the immaturity of the system would incapacitate the operational tests and that the results of the tests would be inadequate.

Surprisingly the system showed some good overall behaviour. We were able to monitor SANJOTEC facilities remotely and proceed with some operational testing. Besides this the immaturity of the system was revealed in several aspects that are worth mentioning to drive future implementations. This is important, not only to reach a commercial-line product, but also so that prototypes are easier to test. In order to validate new approaches and new functionalities in an efficient way, the system must have some supporting functionalities, mature enough, which will form the baseline system. This baseline system will be the framework for testing specific implementations of new functionalities, new methods, and even new EMMON modules.

5.9 Stand-by state

In the current prototype implementation, version DEMMON2, we didn't focus on the operation on the initial state of the mote, in stand-by mode when it is scanning the radio channels looking for its parent beacon. For the purpose of this prototype we just developed a straightforward approach where the mote is constantly listening to the medium, one channel at a time for a time longer than the duration of the beaconing configured for the network. When it finishes listening to the last channel it goes back to the beginning. This scanning cycle continues until it catches the beacon and enters the normal operational state.

This straightforward approach is not power efficient and it is still static – the motes know beforehand who their parent is.

For test-beds that run without batteries (e.g., powered by USB cables) the power efficiency is not important. But for test-beds running on batteries, like the one at SANJOTEC, this assumes some importance and impact on the deployment durability.

5.10 Queries and Alarms State at the network

When we wanted to delete queries to create new ones, we weren't sure that the deletion of the query was completely disseminated. If some node loses connectivity temporarily and during that time a query remove or a new query are disseminated, there is no guarantee that the request is delivered to the nodes as soon as they reconnect to the network.

One possible solution is to implement a mechanism at the Cluster Heads, such that in the case of missing reports or of a report of a deleted query the Cluster Head would resend the request to the Sensor Node.

5.11 Network Administration

From our earlier tests, we really felt the need to have some remote control over the network, in particular, we implementeda number of management commands, such as a logical reset function at the network. This way the network administrator could reset everything and start a new test from a clean instantiation of the system, without having to go to the motes, one by one, performing a physical reset.

The reset of high-level components such as C&C Client, C&C Server and GW is easier, as they are running on full-featured OS with network connectivity like TCP/IP.

Associated with the reset function, let us call it “Over-the-Air Reset”; we have the wireless programming of the motes, what we call the “Over-the-Air Programming” (OTAP). OTAP would allow us to deploy new features and fixes through the network with a minimal downtime and an increased flexibility. The “Over-the-Air Reset” greatly aided the deployment and management of the network.

6. EM-Set – The EMMON Toolset: from Network Planning to Nodes Programming.

In order to help application designers customize the EMMON system parameters [RD-2] and assess whether its expected performance meets the specific requirements, we developed EM-set [RD-4], whose overall perspective is sketched in Figure 2. The ultimate goal of EM-set is to thoroughly evaluate functional and non-functional system properties through several performance indices. For instance, it enables the assessment of EMMON scalability limits through an evaluation of, for example, end-to-end (e2e) delays derived from analytical and simulation models and compared against experimental trials conducted over a physical WSN test-bed.

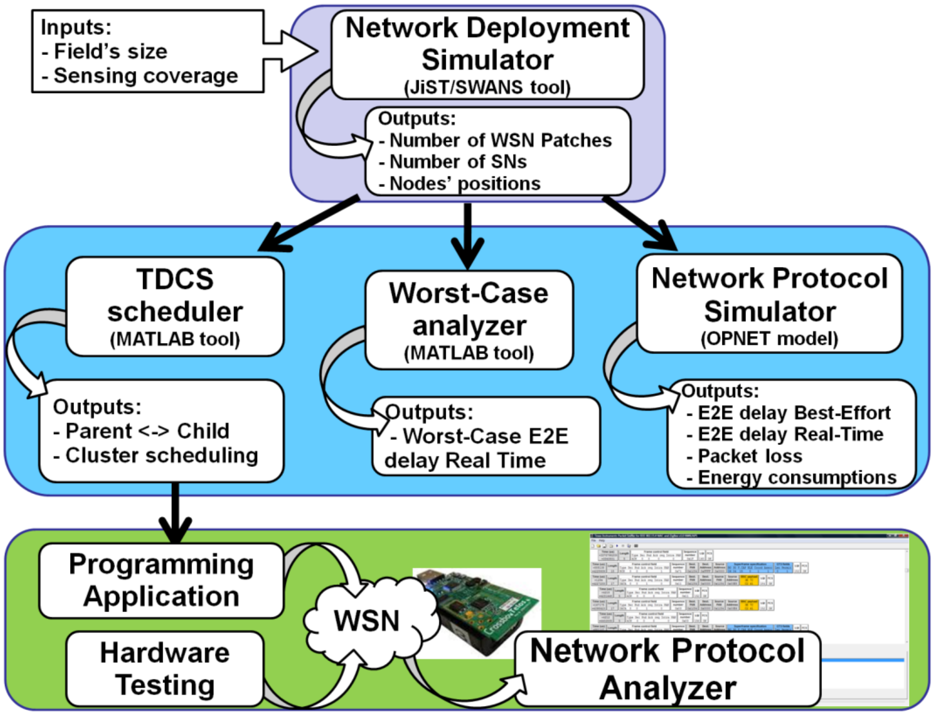

Figure 2: EM-Set - The EMMON Toolset

Starting from (i) the definition of the size of the area to cover with the SNs, (ii) the sensing coverage of each SN and (iii) assuming the atomic structure of a basic WSN Patch, i.e., a GW and N CHs surrounding it, the Network Deployment Planning tool outputs the number of WSN Patches and SNs needed to cover such area, as well as their optimal placement. This output feeds three tools for network dimensioning and performance evaluation: the TDCS scheduler, the Worst-Case analyser and the Network Protocol simulator. Theoretical upper bounds on the e2e delays of real-time traffic are analytically derived, while e2e delays for both best-effort and real-time traffic classes, packet loss ratio and network lifetime are estimated through simulation. Finally, the TDCS scheduler outputs the topology of a WSN Patch and its clusters' scheduling. This information feeds the Remote Programming and Testing tool to program a physical WSN test-bed (e.g., via USB tree). Then the Network Protocol Analyser tool (i.e., the sniffers and an EMMON customized parser) is able to capture the network behaviour to cross-validate the previous analytical and simulation results.

In parallel, we also designed an application to automate the testing of the hardware (USB cabling/hubs and TelosB nodes) having an element as reference (e.g., a previously tested TelosB node or USB hub). This testing tool compares the behaviour of the elements under tests with the reference one. It was fundamental to early identify: (i) 19 out of 300+ TelosB with faulty humidity sensors (i.e., not usable as SNs); (ii) 2 out of 50+ USB hubs broken and (iii) a whole set of (3 m length) USB cables not compliant with the specification given to our local supplier.

7. Conclusions

The main objective of the EMMON project was the development of an integrated framework of technologies to enable large-scale and dense, real-time monitoring of specific natural scenarios using Wireless Sensor Network (WSN) devices.

The first demonstrator, DEMMON1, validated the overall approach of the system, but also highlighted a number of issues, in particularly in terms of usability of the solution: its graphical user interface, and the lack of deployment and management support. These limitation/problems were further improved for DEMMON2. One of the bigger issues had to do with the physical deploying of the motes and the handling needed. This was discussed within D8.3 [RD-5] and D8.6 [RD-22]. However, there are other issues that are more structural and represent a bigger effort. An example of this type of problem is the monitoring objects. Currently, only rectangles aligned with North-South and East-West axis are supported. To allow the monitoring of different polygons, a restructuring of the C&C Client and WSN middleware would be necessary and an overhead should be considered.

Besides the limitations/problems detected, the project achieved good results and provides good indicators to the implementation of a bigger WSN. In particular, a full integrated engineering framework composed by several toolsets has been designed: this allows network designers and system administrators to estimate how the resulting system will behave and how nodes can be placed to cover a given area.

Scalability was the most important objective of EMMON project; this was shown and proven by using more than 400 physical nodes within the SANJOTEC facility, 2600 emulated nodes and by simulation. The overall results for simulation at all layers were:

- Network level (up to 501 nodes per Patch)
- Middleware level (up 11659 nodes)
- Gateway <-> CC level (up 144 Patches)

These results are very encouraging as we can see we can have more than 11000 nodes communicating with each other using the middleware. Overall, the EMMON project has made a significant contribution towards making large-scale wireless sensor networks a reality.

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