Investigation of WSN Applied in the Building Sector

Christian Orthmann

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Technical University of Denmark
Informatics and Mathematical Modelling
Building 321, DK-2800 Kongens Lyngby, Denmark
Phone +45 45253351, Fax +45 45882673
reception@imm.dtu.dk
www.imm.dtu.dk IMM-M.Sc.-2014-

Summary (English)

Building construction and operation is an expensive endeavour where the economy is influenced by energy-efficiency and minimization of errors and damages. In fact correction of errors are responsible for 13-18% of the expenses used in the construction process.[RBWK10] Some errors, like usage of bad or damaged materials and equipment, can be prevented through mobile sensor monitoring. During operation, condition monitoring and active control of technical installations are considered today, but commonly as wired solutions. Effectively it could become advantageous to optimize the resource-efficiency of older buildings and as a result thereby enhance the indoor environment, create savings from operational costs and benefit the global climate.

The goal of this thesis is to simplify development of wireless sensor networks for the building industry by creating a generic model that eases wireless sensor network (WSN) design and targeting all phases of the building process. To do so, the most important design parameters were identified and explained. The performance of each design parameter was then evaluated with wireless sensor units in order to illustrate the limitations and implications of the design choices.

It was argued how relevant network topologies and communication protocols have different advantages and evaluated how (ZigBee) communication range, quality and signal strength are affected in operational buildings.

To ease the use of the generic model, a set of typical node life-cycles were derived which are customizable and provides desired node behaviours.

One of the top concerns regarding WSN design was battery lifetime. It proved to be even more problematic than first anticipated. A model for prediction of battery lifetime was therefore created. Through experiments, it was shown that the battery lifetime predictions were fairly accurate. In connection with building operation it is considered fully acceptable to use external power for the wireless nodes to save battery replacement costs.

In conclusion, the generic model was applied to a real-life case in Sisimiut, Greenland where it was shown that the WSN solution both created economic savings and added technological advantages compared to the standard (wired) solution. Going further, it was indicated that these gains were even more pronounced in remote regions like Greenland, because of the possibility to adjust and configure the system from the internet.

In essence, this thesis describes how to choose network topology, communication protocol, node life-cycle and hardware for wireless sensor network applications in the building industry. It is accomplished through a simple model, which also describes how system requirements may be validated early and thereby avoid faulty design.

Summary (Danish)

Byggeri og dets efterfølgende drift er en dyr affære, når økonomien påvirkes af energieffektivitet og minimering af fejl og skader. Faktisk er korrektion af fejl ansvarlig for 13-18% af udgifterne i byggeprocessen.[RBWK10] Nogle fejl, så som brugen af ukurante eller beskadigede materialer og udstyr, vil kunne undgås ved mobil tilstandsovervågning. I forbindelse med tilstandsovervågning og aktiv styring af tekniske installationer i bygninger overvejes almindeligvis kablede løsninger. Faktisk kan det blive fordelagtigt at optimere ressourceforbruget i ældre bygninger, og som et resultat deraf, forbedre indeklimaet, skabe besparelser fra driftsomkostninger og gavne det globale klima.

Målet med denne afhandling er, at forenkle udvikling af trådløse sensornetværk (WSN) til byggeindustrien, ved at skabe en generisk model, der gør design af trådløse sensornetværk lettere og retter sig mod alle faser af byggeprocessen. For at gøre dette, er de vigtigste designparametre blevet identificeret og forklaret. Resultatet fra hver designparameter, blev derefter evalueret med trådløse sensorenheder, med henblik på at belyse et designvalgs begrænsninger og konsekvenser.

Der er redegjort for, hvordan relevante netværkstopologier og kommunikationsprotokoller har forskellige fordele og ulemper, samt evalueret hvordan (ZigBee) kommunikationsrækkevidde, kvalitet og signalstyrke påvirkes i beboede bygninger.

For at lette brugen af den generiske model, blev der udviklet et sæt typiske brugerdefinerbare node-livscykluser, som giver en ønsket node-opførsel.

En af de største bekymringer vedrørende udvikling af WSN er batterilevetid,

hvilket viste sig, at være endnu mere problematisk end først antaget. Der blev derfor skabt en model til forudsigelse af batteriets levetid. Gennem eksperimenter, blev det vist, at modellens forudsigerlser af batterilevetiden var rimeligt præcise. I forbindelse med drift af bygninger anses det dog for helt acceptabelt, at bruge ekstern strømkilde, til at drive de trådløse noder for at undgå omkostninger til udskiftning af batterier.

Til sidst blev den generiske model anvendt på et problem i Sisimiut, Grønland, hvor det blev vist, at den foreslåede WSN løsning både ville skabe økonomiske besparelser og tilføje teknologiske fordele i forhold til den normale (kabel) løsning. Herudover blev det nævnt, at disse fordele var endnu mere markante i fjerntliggende regioner, som Grønland, på grund af muligheden for at tilpasse og konfigurere systemet over internettet.

Essentielt beskriver denne afhandling, hvordan man vælger netværks topologi, kommunikationsprotokol, node livscyklus og hardware til trådløse sensornetværk, som kan anvendes i byggeindustrien. Det bliver opnået gennem en simpel model, som også beskriver, hvordan systemkrav kan valideres på et tidligt tidspunkt for dermed at undgå fejlagtigt design.

Preface

This thesis was prepared at the department of Applied Mathematics and Computer Science in cooperation with the department of Civil Engineering at the Technical University of Denmark in fulfilment of the requirements for acquiring a M.Sc. in Digital Media Engineering. The project has been completed in the period between 26-September-2013 and 26-February-2014, where Associate Professor Alfred Heller has been supervisor for the project.

The thesis deals with wireless sensor network and its application to the building industry.

Related to this thesis, I recently had a paper published in Energy and Buildings (ENB), which was written in cooperation with Associate Professor Alfred Heller.

The thesis consists of a guideline how to choose network topology, communication protocol, node life-cycle and hardware for wireless sensor network applications. Furthermore, it contains a case story where a ventilation problem in a building located in Greenland is considered.

As a result of the thesis case story, I also recently had a conference paper accepted for the International conference - Artek Event 2014, which was written in cooperation with Associate Professor Alfred Heller and Ph.D. student Martin Kotol.

Lyngby, 26-February-2014

Christian Orthmann

Christian Orthmann

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On behalf of everyone involved, I would also like to thank the *Bjarne Saxhofs Fond* for its financial funding that made this project and a solution to the ventilation problem at the Apisseq dormitory possible.

Finally, I would like to thank my family and friends who have been a great source of support whenever I needed it.

Contents

Chapter 1

Introduction

In the recent years, "green building" have become a popular term associated with buildings that are designed to be environmentally responsible and energy efficient throughout the building process - from prefabrication of materials to demolition of the building.

Common characteristics of a green building is that it focuses on:

Resource-Efficiency in terms of water, heat, ventilation, energy and other resources, to reduce operational costs in an environmentally friendly way.

Indoor Environment Optimization as a way of enhancing comfortability and productivity of the residents.

Waste Reduction to help prevent environmental degradation.

A criticized issue with green building is the price. The criticism is founded in the fact that the up-front cost of a green, or environmentally friendly, building is higher than the alternative. The counter argument is that it is a trade-off between up-front and operational costs where investments in green building, according to [KAB+03], yield substantial savings over life of the building.

These savings are mainly a result of reduced costs in the *Operation* phase due to resource-efficiency; achieved by dynamically adjusting the energy use of the building through sensor technology.

Sensor technology is not new to the building industry. In fact most buildings today are subject to some form of sensing. Examples of existing building sensing applications could be: home surveillance, monitoring and control, home automation. Today, building sensor technology is commonly wired meaning that the sensors communicate through wiring in the building.

The purpose of this thesis is therefore to investigate the advantages and effects of introducing wireless sensors, and more specifically Wireless Sensor Networks (WSN), to the building sector.

Beside seamless installation of sensors and improvement of resource-efficiency, a possible advantage of wireless sensor networks is early discovery of problems and errors in the building process. For instance, early discovery and discarding of weakened materials, before use, would prevent the more costly expense of correcting and strengthening the construction later.

In terms of costs, correction of errors covers 13-18% of the expenses used in the construction process[RBWK10] meaning that detection and prevention of errors could lead to even greater savings.

1.1 The Building Process

The building process, illustrated in Figure 1.1, describes the life-cycle of a building from prefabrication of building components to demolition. Each phase in the building process uniquely describes the state of the building in the life cycle.

In the following, the introduction of the WSN technology into the individual phases of a building process is proposed (through cases).

Prefabrication of building components by industrial means are increasing. The process and quality can be monitored on the basis of sensors. An example could be to embed temperature and moisture sensors in order to monitor and document the drying process of concrete elements under the production process

Transportation from the fabrication to the construction site may imply incidences that may have an impact on the quality of the product. On the other hand, the documentation of proper handling can also be documented on basis

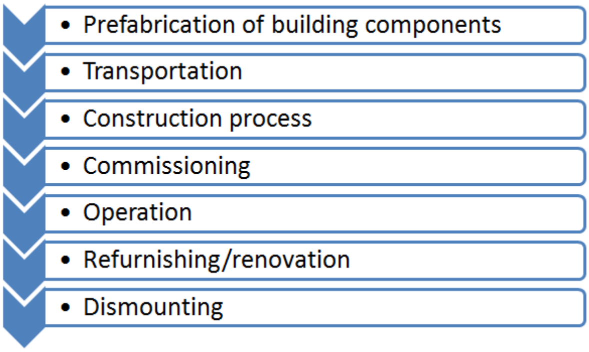


Figure 1.1: Phases of a building life-cycle

of sensors.

Construction of buildings can be improved by the introduction of sensor technologies. Space at construction sites is very limited and must be utilized optimally. When large materials, such as concrete elements, are entering the construction site, sensors with identification can be used to monitor if the elements ought to be delivered at the given date at all. Mistaken deliveries can be sent back and space saved. A second example could be an assembly case, where concrete elements are to be joined. In this case identities of elements and joints would make it possible to alert mistaken assembly attempts.

Commissioning would be supported by identification of the involved elements to be linked to BIM-descriptions under commissioning process. Potential errors could easily be located, identified and documented.

Operation is the longest phase of a building. Here, sensors can be part of the overall monitoring and control system. Extension, replacements and removal of sensors could be done dynamically with no interruption of the system. This advantage is in itself a valuable improvement of the overall system.

Renovation and other refurnishing tasks would be supported similarly to the construction processes.

Dismounting is made easier due to the identification of components. Assuming information related to the identification, the material data, handling and disposal data of the components could be communicated by sensors themselves, or through correlation to databases.

Chapter 2

Wireless Sensor Network

A Wireless Sensor Network (WSN) is as the name hints a network of sensors. It consists of distributed nodes that monitor environmental or physical conditions like humidity and temperature through sensors.

Communication within a WSN commonly happens by **Message Passing** (or **Hops**), thus enabling nodes far apart to communicate; even though they are outside mutual communication range. That said, this functionality is dependent upon applying a suitable communication protocol and network topology in the network.

A WSN can consist of different types of nodes; though not always every type, depending on the application, scale and applied network topology. The following gives a brief introduction to the terminology used in this thesis.

Synchronization Node A node which collects data from other nodes in the network and possibly sends the synchronized data to a PC or server. Synchronization nodes may also be called Terminals or Gateways.

Router Node A device used to route messages to and from nodes in the network.

Sensor Node A device collecting data through sensors and possibly sends collected data to synchronization nodes.

The terms are very general where the individual hardware and sensors typically are selected as needed. A wireless sensor network can also consist of different kinds of nodes from each node type. The WSN may for instance be spread over both land and under water; in which case, one may have decided to use one kind of sensor under water and another kind on the surface. A general argument could be that different sensor readings would be of interest in different areas.

2.1 Initial Experimental Setup

In January 2013, the initial experiments with the Wireless Sensor Network (WSN) technology was concluded and later published in [HO14]. The Sun Small Programmable Object Technology (SPOT) was used for implementation of the WSN and used as a proof-of-concept for the feasibility. Figure 2.1 illustrates an overview of the experimental setup used in the experiments.

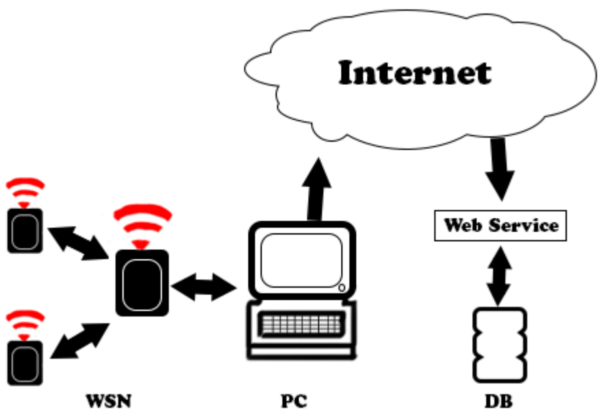


Figure 2.1: Phases of a building life-cycle

As it can be derived from Figure 2.1 a wireless sensor network (WSN) is communicating with a PC, which synchronizes communications through the internet to an online web service which stores and analyses the data.

2.1.1 Cases

The experimental setup was applied to the following cases to demonstrate the application of sensors in the building process. Each of the cases was focused on solving a problem that may provide economical, technical or social gains in the building life cycle described in Section 1.1. Additionally each case investigated the technical feasibility through implementation.

2.1.1.1 Measurements and online access

The purpose of this experiment was to show that measurements in a WSN can be collected, stored on a server and made accessible through an online web service.

Usage
In regard to the building process, such functionality could be used to detect if materials are subjugated to unwanted conditions; such as hard impacts or freezing temperatures. In response, it would be possible to alert the appropriate people through online services if sensor readings suggests unwanted levels.

Results
It was discovered that the ability for a node to communicate through each other, as hops, to the synchronization node was very important; since it enabled all the nodes in the network to reach the synchronization node - even if it was outside the range of the individual node. This also made it possible to send commands to all nodes in the network directly from the synchronization node.

Additionally, the sensor readings on the Sun SPOT platform proved to be fairly inaccurate, which revealed that sensor quality should be evaluated to verify if a sensor is accurate enough for a given use case.

2.1.1.2 Conditions

The purpose of this experiment was to investigate if nodes in a WSN can be used for surveillance of predetermined sensor and node conditions.

Usage
In relation to the building process, this functionality would make it possible to detect and record incidents, such as impacts, moisture or freezing temperatures, during transport, at the construction site or after construction. In response an

incident report can be sent to warn about possible damage; thus minimizing faults in the building process; lower the time and costs of construction; and save future owners grievance from property damage.

Results
It was discovered that conditions with Sun SPOTs works by checking each condition at predefined intervals (or constantly). In essence this meant that the SPOTs doesn't *respond* to events but rather *looks* for events. Consequently, this creates an issue related to battery lifetime and impact detection; where short impulse events, like impacts, may be missed unless the condition is checked constantly, which dramatically reduces the battery life. It was suggested that a *semi-sleeping* state which turns off most hardware only powering the accelerometer used for impact detection, would offer an acceptable compromise to the issue. However, this solution would require use of a platform that supports such functionality.

2.1.1.3 States

The purpose of this experiment was to prove that a node in a WSN can be programmed as a state machine; changing behaviour based on the active state.

Usage
In regard to the building process, this ability would provide the foundation required for a node to adapt to each phase in the building process; thus allowing it to be used in and optimized for multiple phases. This functionality would be at the core of optimizing power consumption and extending node lifetime; by only powering relevant hardware in each state and adjusting node life-cycle.

Results
It was discovered that memory-use and persistent-storage is important concerns that limits the amount of data that can be held by a node at any given time. As a solution, nodes may therefore use selective data-storing in phases, like transportation, where immediate offloading of data is impossible. More specifically, this means that a node only records critical events during such phases. In case of transportation, it would therefore only record events that breaks predefined conditions, like hard impacts or freezing temperatures.

A noteworthy challenge with this functionality is how transition between states should be invoked in a node. In this, the possible means of transition would depend on the phases in which the transition begins and ends. For instance, a node may invoke a transition passively when network is within reach; or through commands sent by the synchronization node; or even by manually interacting with a node.

2.1.1.4 Positioning

The purpose of this experiment was to show that positioning techniques can be applied in a WSN to passively identify the positions of all nodes in the network from a selected set of known node locations.

Usage
Positioning in a WSN on a building site would provide a real-time view of the building site with locations of items and materials of interest. Combined with a description of how materials is intended to be grouped, it would be possible to warn appropriate staff if materials or items are misplaced; depending on the situation it may be a priority to ensure it is relocated to avoid conditions that may damage the item or material. In addition to this, it would be possible to detect if delivered items enter the building site too early or if items are leaving unauthorized - maybe due to theft.

Results
It was discovered that it was easiest to perform positioning through *lateration* techniques, such as *Time-of-Arrival* (ToA) and *Reverse Signal Strength* (RSS), in a WSN; partly due to minimal hardware requirements. To perform RSS or ToA positioning two basic requirements must be met; 1) the antenna should be omnidirectional and 2) the hardware should have a *Reverse Signal Strength Indicator* (RSSI).

The ToA approach is closely dependent on the ability to measure time. Being a distributed system, global time and clock-synchronization proved to be important issues that must be solved for this technique to work. Though trials did give consistent time measurements, it were discovered that there weren't enough difference in measurements to decide actual distances with SPOTs separated by distances of less than 2.5 meters.

The RSSI approach proved to be dependent on the quality and reliability of transmission signal strength and RSSI readings. The RSSI technique showed more promise than the ToA approach as there were definite changes in signal strength over short distances.

The trick about RSSI and ToA is how to translate the values to indicate real distances; though more advanced approaches are possible, the simplistic solution of mapping averaged values to known distances were used.

2.1.2 Conclusion and Future Work

In conclusion, the experiments indicates that it is technically feasible to utilize wireless sensors in network throughout the building process. That said, a lot important issues were identified and solutions should be considered carefully in preparation for further development.

In addition, arguments were made that suggests implementation of wireless sensor networks in the building cycle will lead to economical, technical and societal gains if the technical issues are solved. Moreover, significant advantages were found in having the data accessible through internet services, where many convenience features suddenly became possible and opportunities for further gains became possible. Among the most important was the ability to warn the appropriate personnel directly under critical circumstances.

In regard to future development, it was discovered that the quality and type of antenna and RSSI are of immense importance when dealing with positioning. Furthermore, sensors should be able to react to sensor readings rather than check conditions periodically, if measurement of impulses are considered important. It would also be interesting to look further into the aspect of battery lifetime and learn how long battery lifetimes best can be achieved in a WSN for the building process.

To achieve these goals a new platform must therefore be found; which is able to solve the issues experienced with the Sun SPOT platform.

2.2 Investigation of WSN Platforms

During the summer of 2013, an investigation was therefore made to describe and compare available solutions to WSN development; both including commercial products and custom hardware approaches. As part of the investigation, it was then evaluated how suited each platform to continue the work described in Section 2.1 and hence the building process.

2.2.1 LORD MicroStrain

Lord MicroStrain develops a range of sensors and terminals which are used in a wide range of commercial industries [Mic]. All of their existing solutions provide different advantages in regards to the given use case, and *Lord MicroStrain* also provide the possibility of creating a custom system for specific purposes.

Table 2.1 lists the overall pros and cons of the *Lord MicroStrain* platform.

Pros	**Cons**
Over-the-air programming	Proprietary communication protocol
Wireless sensing system software	Expensive
LabView support	SensorCloud (is a paid service)
SensorCloud (functionality)	No open-source policy

Table 2.1: The pros and cons of LORD MicroStrain

2.2.2 National Instruments

National Instruments provide, much like *Lord MicroStrain*, many different solutions which are used in a long range of commercial industries [Ins]. The hardware itself is highly adaptive, since any given compatible sensor can be connected, thus adapting the platform to a given use case.

Table 2.2 lists the overall pros and cons of the *National Instruments* platform.

Pros	**Cons**
Over-the-air programming	Expensive
LabView support	No open-source policy
On-node calculations	
Web-Based Visualization and Analytics	
Highly adaptive hardware	

Table 2.2: The pros and cons of National Instruments

2.2.3 Libelium Waspmote

Libelium provides a sensor platform named *Waspmote*, which is different compared to the two previously mentioned products, as it more is modular; making it easy to customize each node in great detail. The *Waspmote* platform offers a range of different *Sensor Boards* designed for specific use cases; supporting relevant sensors[Libc]. Alternatively, custom sensor can be developed supporting a custom set of sensors. Due to the high amount of customizability, the *Waspmote* platform is used in many different commercial solutions [Liba].

Table 2.3 lists the overall pros and cons of the *Libellum Waspmote* platform.

Pros	**Cons**
Over-the-air programming	Relies on sensor-boards from Libellum
High customizability	
Toggle any sensor interfaces / radio modules	
Easily exchangeable wireless interfaces	
Easily exchangeable sensor boards	
Supports multiple wireless interfaces	
Great support / learning center	
Open-source policy	

Table 2.3: The pros and cons of Libelium Waspmote

2.2.4 Custom Node

In the *Custom Node* approach, the intent is to build WSN nodes from scratch. Table 2.4 lists a node hardware specification example.

Product	**Approximated Cost (USD)**
TI MSP430 (LaunchPad Board)	10.0 $
TI CC2420 / CC2430 / CC2431 (ZigBee)	15.5 $
Battery pack (unspecified)	(Unknown)
Sensor (unspecified)	> 2 $
	COST = 27.5 $

Table 2.4: Minimal Hardware Specification for Custom Node

To develop the custom node approach further devices and parts may be required for programming and installation. Among other things this includes an USB Debugger (FET) and casing for the sensor nodes.

A WSN terminal could likewise be created from scratch based upon the sensor node recipe. Alternatively a Raspberry Pi with a ZigBee (XBee) module may also do the trick. The pros and cons of this approach is as follows:

Pros	**Cons**
Highly customizable	Everything must be built from scratch
Low cost	No technical support
More control of the system	

Table 2.5: The pros and cons of building a custom system

2.2.5 MakeThisWork ApS

MakeThisWork [Sø] is an experimental platform, and is as of this writing currently a prototype. It is intended as a plug-and-sense platform, where many different sensors easily can be exchanged and tested. Though, outside its original purpose it would be possible use *MakeThisWork* prototypes as nodes in a WSN.

The *MakeThisWork* platform is based on Bluetooth Low Energy, which means that the battery consumption is low, but a mesh-network is not easily obtainable. That said, it would be fitting for a star-network with a central terminal for persistent storage and/or server communication.

Pros	**Cons**
Technical support	High cost
More control of the system	Unreleased prototype
Highly customizable	Missing community and documentation
Bluetooth Low Energy	Mesh-network not easily obtainable
Open-source policy	
Easily exchangeable sensors	

Table 2.6: The pros and cons of the platform from MakeThisWork

According to the founder of *MakeThisWork*, the prototype hardware is expected to cost approximately 6,000 DKK.

2.2.6 Supported Cases

Table 2.7 lists to which extent the highlighted platforms supports the cases from Section 2.1.1. The information in Table 2.7 and 2.8 were derived from available documentation for the respective platforms.

Platform	Measurements	Conditions	States	Positioning
LORD MicroStrain	YES	YES	PARTIALLY[1]	YES
National Instruments	YES	YES	YES[2]	MAYBE
Libelium Waspmote	YES	YES	YES	YES

Table 2.7: Platform Use Case Support

[1]: only node *ON* and *SLEEP* states available.

[2]: state manipulation is possible, but the extent of configuration is not confirmed.

Table 2.8 describes if the respective platforms supports the desired features needed to rectify the shortcomings discovered with the Sun SPOT platform.

Platform	RSSI	Wake on Events	Toggle Hardware Parts
LORD MicroStrain	YES	YES	NO
National Instruments	YES	NO	YES
Libelium Waspmote	YES	YES	YES

Table 2.8: Platform Desired Feature Support

2.2.7 Discussion

After evaluating both commercial and custom solutions there appear to be a clear trade-off between customization, flexibility/modularity, support and pre-configured services (features).

Commercial solutions typically offer technical support, a wide range of out-of-the-box features and forums dedicated to troubleshooting. In addition, commercial solutions often offer a level of abstraction in relation to system development, thus allowing the developer to avoid low-level programming. A common drawback of commercial solutions is their frequent use of proprietary protocols, making it harder to integrate third-party hardware with the system.

Custom solutions typically offer more control of the system, but is far more time-consuming to develop. This is partly due to the lack of out-of-the-box features that often are present with commercial solutions. Furthermore, if nodes should be created from scratch, the solution will require a very low-level development approach.

While commercial products might speed up development through a higher level of abstraction and out-of-the-box features, it is typically at the cost of control and flexibility. However, some cases require special features that might need more control than commercial solutions offer.

It is therefore often a question of how fine-grained control there is needed, compared to time invested on implementing functionality that might have been easier to come by with a higher level of abstraction.

2.2.8 Conclusion

It was found that the commercial products had good support features and software suites, which would have to be developed separately for custom approaches. That said, it is a trade-off as the cost of commercial WSN solutions, in terms of hardware, is far more expensive than creating a custom system. However, development time should not be discounted, since the higher hardware cost may be compensated by saved time in developing the system.

In the light that this project is experimental and on a deadline, a high customizability is of the utmost importance, at the same time as dependent upon rapid development. It is therefore not optimal to start developing a new platform from scratch, but attempting to build upon a commercial platform.

Three respected commercial WSN platforms produced by *LORD MicroStrain*, *National Instruments* and *Libelium* respectively where highlighted.

Reviewing the commercial platforms revealed that the *Libelium Waspmote* platform was both the cheapest and the most customizable. Coincidently, this platform was also the only of the three that definitely could satisfy all the use cases and desired features specified in Section 2.1.1. That being said, the commercial products can be customized by the respective firms in short production cycles if large quantities are ordered.

That being said, it should be mentioned that the respective firms offer the possibility of producing custom

A further advantage of the *Libelium Waspmote* platform was that it supports multiple and easily exchangeable wireless interfaces; meaning that it is easy to fit the resulting system with the optimal wireless interface for each use case. Also, it makes upgrading an existing system much more seamless, which can be required as backwards compatibility may be an issue when using certain communication protocols (See Appendix C).

In conclusion it was therefore decided to use the *Libelium Waspmote* platform in this thesis and for future development.

Chapter 3

Problem Definition

In the aim of simplifying development and hopefully motivate introduction of wireless sensor networks in the building industry, the purpose of this thesis is to create a generic model that ease wireless sensor network design; targeting each of the building process phases.

Although wireless sensor networks can be used to introduce innovative services to commercial applications in areas like the building industry, the technology has limitations and challenges that needs to be considered in the application design. To mitigate these challenges, the network must be carefully designed with special regard to network topology, communication protocols and performance expectations - like communication range and lifetime expectancy. From this point onwards, these parameters will be called *Design Parameters* as they reflect the most crucial choices for designing a WSN and consequently creates the foundation of the generic model.

The performance of each design parameter will be evaluated with the Libelium Waspmote platform in order to illustrate the limitations and implications of the design choices.

As the outcome of this thesis, the generic model is actually applied to a real-life case in Sisimiut, Greenland where the resulting system is compared to the standard (wired) solution.

Chapter 4

Design Parameters

To create a generic WSN design model for the building industry, it is important to explain the relevant choices for each *Design Parameter* and discuss the potential consequences and benefits.

4.1 Network Topologies

In distributed systems, it is important to choose a network structure which accommodates the system requirements that relates to connectivity, network coverage, latency and throughput.

The most common network structures or *network topologies* have been named and defined within network theory. The following sections will briefly describe the topologies used in this thesis.

4.1.1 Star

In a star-network all communication is routed through a single hub or terminal with a resulting pattern as illustrated in Figure 4.1.

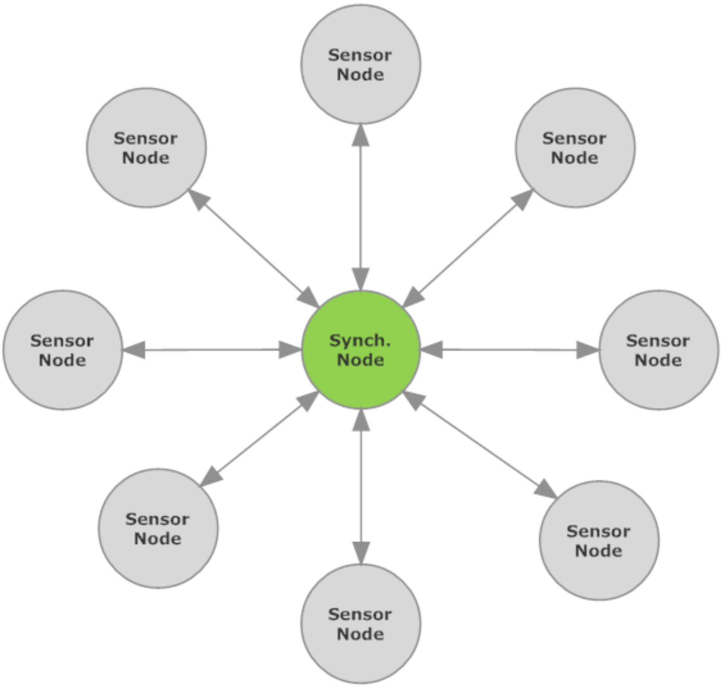


Figure 4.1: Star network topology

Within a star-network, the coverage equals the communication range of the terminal with the result that communication only can be passed between nodes in range of the terminal.

Table 4.1 lists the pros and cons of the star topology in relation to WSN development.

Positive	Negative
Performance: no intermediary hops	Vulnerability: dependency on synch. node
Centrality: easily extensible	Scalability: dependent on synch. node specs.
Simplicity: no complex routing	

Table 4.1: Star topology: pros and cons

4.1.2 Mesh

The mesh-network topology is signified by its ability to send messages through links in the network which is also called *Hops*.

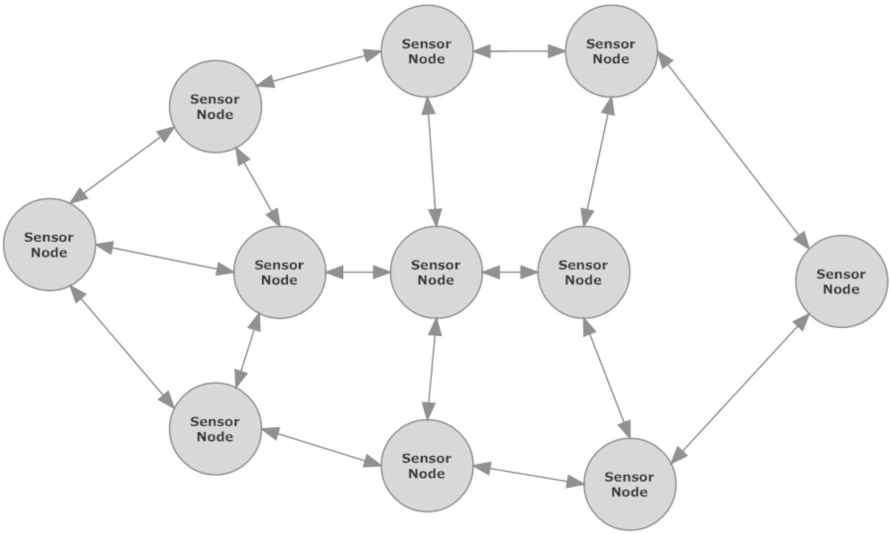


Figure 4.2: Mesh network topology

Within a mesh-network the coverage equals the area covered by the linked nodes and terminals; meaning that any node in the network can communicate with any other node connected to it through network links.

Table 4.2 illustrates the pros and cons of the mesh topology in relation to WSN development.

Positive	**Negative**
Extensibility: easy	Performance: many intermediate hops
Mobility: good when nodes are mobile	Standards: few available protocols
Self-healing: no single node dependency	Network might split

Table 4.2: Mesh topology: pros and cons

4.1.3 Daisy Chain

In a daisy chain network the nodes are connected in a series where each node is linked to the next in the series. Messages are then passed through the network, as illustrated on Figure 4.3, by forwarding the message down the line until the intended recipient is reached.

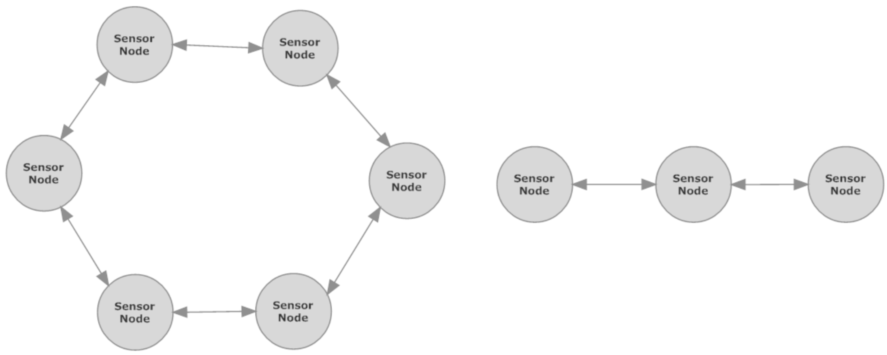


Figure 4.3: Daisy Chain network topology

As shown on Figure 4.3, there are two basic forms of a daisy-chained network: linear and ring.

The daisy chain topology is one of the simplest ways to arrange nodes in a network, but it has a few weaknesses that are important to consider. For instance are chained networks prone to crippling network failures when a node fails. It is therefore important to consider how the network can repair itself in case of failures.

Table 4.3 illustrates the pros and cons of the daisy chain topology in relation to WSN development.

Positive	Negative
Simplicity: no need for connectivity management	Vulnerability: breaks upon node failure
Cost: cheaper than other topologies	Performance: slow
Extensibility: easy	Scalability: best in small networks
Installation: easy	Static: may break due to node movement

Table 4.3: Daisy Chain topology: pros and cons

4.1.4 Tree

The tree topology is a hierarchical network structure that branches out from a "root" node at the top of the hierarchy. The tree is not constrained to a number of hierarchy levels and each node is allowed to connect with one "parent" and one or more "children" in the hierarchy. Figure 4.4 gives an example of a tree structure.

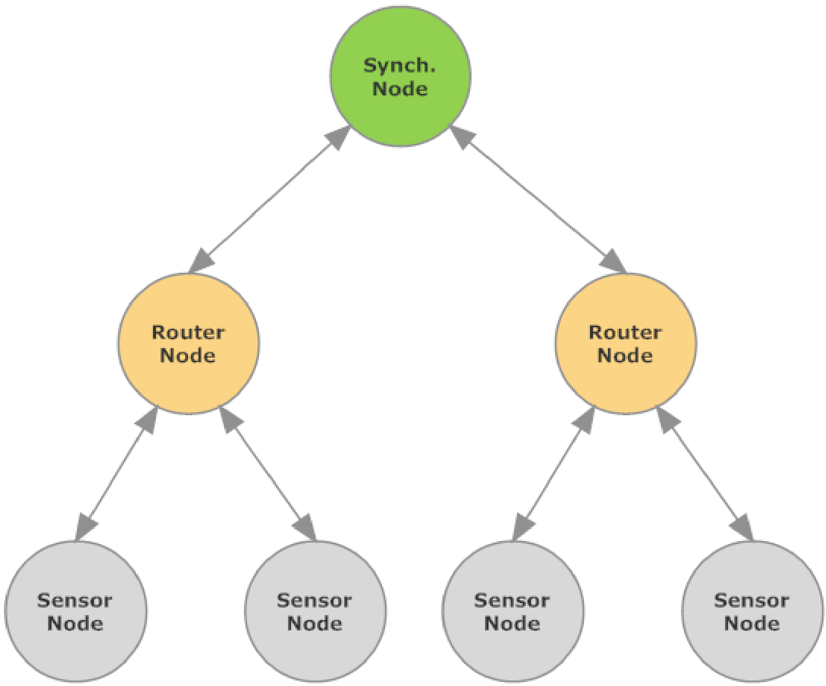


Figure 4.4: Tree network topology

The network coverage is equal to the area covered by the communication range of linked nodes in the network. One of the weaknesses of the tree-structure is that it is prone to critical failures if a node high up in the hierarchy fails. Like for the *Daisy Chain* topology, it is therefore important to consider how to repair the network if critical failures are probable or might produce severe consequences.

Table 4.4 illustrates the pros and cons of the tree topology in relation to WSN development.

Positive	Negative
Extensibility: easy	Vulnerability: dependent upon upper hierarchical nodes
Segmentation: easy management and maintenance	

Table 4.4: Tree topology: pros and cons

4.2 Communication Protocols

Communication protocols are needed for computers to communicate and are in essence a set of rules for data exchange between systems. By setting the rules, a protocol enforce a procedure for exchanging data, often with regard to security, reliability and related aspects. A communication protocol may, for instance, guarantee that a message is delivered by incorporating a retry-sequence or guarantee that a message is delivered exactly-once. In wireless networks, the concept is the same, only differentiated by transmission through wireless signals rather than internally or through cables. Commonly a wireless interface is designed for one specific or multiple related protocols meaning that the choice of communication protocol influences hardware requirements.

Going further, differences between communication protocols and interfaces influence the suitability in regard to network structures (or topologies). It is therefore crucial to select a wireless interface and protocol that is well suited for the desired network structure.

To simplify the design parameter, a selection of relevant communication protocols to WSNs are briefly explained in the following. That being said, due to the multitude of available protocols, other relevant choices do exist. The *Z-Wave* protocol is a good example, which is not included in this thesis.

4.2.1 IEEE 802.15.4

IEEE 802.15.4 is a standard for wireless personal area network (WPAN) and it is the basis for protocols like *ZigBee* and *DigiMesh* which often are used in commercial WSNs. The 802.15.4 protocol is suited for applications that require a low data rate and long battery life. That explains the popularity of the standard in relation to WSNs.

There are two types of nodes in a 802.15.4 network: full-function devices (FFDs) and reduced-function devices (RFDs). A FFD is allowed to communicate with any other device and may serve as a common node or be used to relay messages: in which case it is dubbed a coordinator. Though FFDs may relay messages actual routing, and hence multi-hop communication, is not directly supported because the standard doesn't specify a network layer. In comparison, RFDs can only communicate with FFDs and are intended to be simple devices with limited need for communication. Considering the general node types defined in Chapter 2, it can be said that RFDs only may act as *sensor nodes*, whereas FFDs also are allowed to act as *synchronization nodes*. With these node types, the protocol is most suited for the *Star topology* with a central synchronization node or as a peer-to-peer network.

In a 802.15.4 network the minimal security mode is the *MAC mode* which can use access-control-lists for message-acceptance based on the source MAC address. That said, higher levels of security are possible where payloads may be encrypted and access-control-lists may restrict communication to a group of devices or peer-to-peer link.

4.2.2 ZigBee

ZigBee protocol extends the *IEEE 802.15.4* specification by adding a network and an application layer to the protocol. Though both important the network layer is of particular interest as it makes routing and thereby multi-hop communication possible. Beside the new layers, the most significant improvements compared to *802.15.4* are regarding security and network management with the introduction of new tasks like device discovery, management of network join requests and device roles. Being an open standard, the ZigBee protocol also has potential for interoperability between devices from different vendors and simplifies development through established profiles for common applications including energy management and control systems.[Dig08]

There are three node types in a ZigBee network: coordinators, routers and end devices which essentially are based on the node types described in the *IEEE 802.15.4* specification. Considering the general node types defined in Chapter 2, it can be said that coordinators corresponds to synchronization nodes, routers to router nodes and end devices to sensor nodes. These node types makes the protocol well suited for the *Tree* and *Star* topologies with a central synchronization node. A worthwhile comment on the ZigBee specification is that end devices (sensor nodes) are the only nodes allowed to sleep since coordinators and routers must be available for message passing at all times. This might be problematic for some applications, because routers and coordinators may require direct power supply to avoid fast depletion of batteries and, thereby, dissolution of the network.

However, there have been problems with backwards compatibility of the ZigBee protocol across all three versions (e.g. ZigBee 2004, 2006 and PRO).[Bac] Depending on the case, it is therefore either impossible or requires careful design to make devices operating on different versions work together. The most recent ZigBee version is *ZigBee PRO* which is backwards compatible with *ZigBee 2006* assuming that *ZigBee 2006* devices only act as end devices in a *ZigBee PRO* network and vice versa.

4.2.3 DigiMesh

DigiMesh is a proprietary networking protocol, developed by *Digi*, that builds upon the *IEEE 802.15.4* specification. As indicated by the protocol name, it provides the possibility of using the *Mesh topology*.

There is only one node type in a DigiMesh network which may act as any of the general node types defined in Chapter 2. The distinct advantage of a DigiMesh network is that all nodes are allowed to sleep unlike in *802.15.4* and *ZigBee* networks. Additionally, it also simplifies network expansion as all nodes are of the same type and increases robustness by avoiding hierarchical dependencies. However, the main drawback of the protocol is that it does not have the same potential for interoperability with devices made by different vendors, because it is proprietary.[Dig08]

4.2.4 Bluetooth

Bluetooth is a protocol for wireless personal area networks (WPAN) and is often used in computers, headsets and mobile phones. Bluetooth is suited for applications that require a high data rate, short communication range and long battery life. It is rarely used in commercial WSN solutions due to its short communication range and limited scalability, but it offers some intriguing possibilities in regard to interaction with other appliances like phones and cars. These interaction capabilities and recent improvements in power consumption have made Bluetooth more attractive to WSNs.[ELD08] Especially the *Bluetooth Smart (Bluetooth v4)* specification may be of interest to some WSN solutions with its inclusion of Bluetooth *High Speed* and *Low Energy* protocols which for example are applied in fitness, health-care and home information and control applications.[MDDK12]

A Bluetooth network typically consists of a set of peer-to-peer connections which makes it best suited for the *Star topology* with a central synchronization node or as a peer-to-peer network.[Bak05]

An advantage of the Bluetooth protocol is that it is fully backwards compatible[Bac], which simplifies upgrades and interaction with third-party devices.

4.2.5 Wi-Fi

Wi-Fi is a collection of standards for wireless local area networks (WLAN) based on the *IEEE 802.11* specifications. It is widely used and is for example an integral part of smartphones, tablets and laptops. Wi-Fi is well suited for applications that require a high bandwidth and data rate. Wi-Fi-based wireless sensor networks is a new kind of technology which has gained traction with the increasing interest in the Internet of Things. A Wi-Fi-based WSN is therefore capable of realizing applications, like video monitoring with much better results compared to 802.15.4-based systems.[LXKK11]

A Wi-Fi network typically consist of wireless stations and access points. Considering the general node types defined in Chapter 2, it can be said that wireless stations correspond to sensor nodes in a WSN, whereas access points act as synchronization nodes. This makes Wi-Fi best suited for the *Star topology* with a central synchronization node or as a peer-to-peer network.

4.2.6 Overview

For easy reference, Table 4.5 illustrates the protocol suitability with each topology.

Protocol	Daisy-Chain	Star	Tree	Mesh
802.15.4	YES	YES	NO	NO
ZigBee	YES	YES	YES	NO
DigiMesh	YES	YES	YES	YES
Bluetooth	YES	YES	NO	NO
Wi-Fi	YES	YES	NO	NO

Table 4.5: Communication protocol topologies

Table 4.6 a quick overview of the expected performance of each communication technology.

Beyond the advantages mentioned in previous sections, each protocol has the capability to provide the features listed in Table 4.7; which may be of interest to WSN applications in the building industry.

Parameter	802.15.4	ZigBee	DigiMesh	Bluetooth	Wi-Fi
Power consumption	Low	Low	Medium	Medium	Medium
Data rate	20-250 Kbps	20-250 Kbps	10-250 Kbps	1 Mbps	72 Mbps
Max payload	118 bytes	80 bytes	256 bytes	64 Kb	2312 bytes
Communication range	10-100 m	10-100 m	10-100 m	1-10 m	10-100 m
Security	Medium	High	Medium	High	High
Scalability	High	High	High	Low	Medium

Table 4.6: Communication protocol performance[PDYC08][Bak05][Dig08][LSS07]

Feature	802.15.4	ZigBee	DigiMesh	Bluetooth	Wi-Fi
Over-the-air programming	YES	YES	YES	NO	YES
Home appliance interaction	YES	YES	NO	NO	NO
PC, Tablet and phone interaction	NO	NO	NO	YES	YES
Vehicle (car) interaction	NO	NO	NO	YES	NO

Table 4.7: Features with communication protocols

4.3 Communication Range

Though communication protocols may specify rules to guarantee delivery of messages, it is naturally only possible when a communication link exists between the sender and recipient. In wireless networks, communication links are dependent upon the range of antennas to ensure connectivity and therefore reliant on communication range to create the desired network structure. Consequently, it is important to estimate the communication range to prove the feasibility of a given wireless (sensor) network. Unfortunately, wireless signals can be influenced in many ways[BTV+10], but most prominently by:

Environmental conditions like temperature, pressure, electrical noise and magnetic field disturbances which may influence signal strength (communication range)

Objects in the environment like walls, floors or people which may influence signal strength (communication range)

Other wireless signals from devices like routers, mobile phones or other wireless appliances which may influence signal strength (communication range)

It is therefore necessary to test the communication range of the device(s) intended for the wireless setup at the intended location or a similar one prior to installation. By doing so, it will be possible to provide a reasonable communication range estimate and thereby prove the validity of the suggested setup.

However, establishing a connection between two nodes is not enough to guarantee reliable communication. To guarantee reliable communication, the quality of the connection must therefore be evaluated. Received signal strength indication (RSSI) and packet error rates may be helpful as means of evaluating the connection quality. Such evaluation would assume correlation between signal strength and packet loss as the basis for the quality assessment. As established in [ZG03], a high signal strength generally corresponds to low packet loss, though low signal strength does not necessarily correspond to high packet loss.[ZG03] This means that connection quality based on signal strength may indicate where a connection is reliable, but not where it is unreliable. However, using RSSI in combination with packet error rates should mitigate such issues and thereby identify unreliable connections as well.

4.4 Node Life-cycle

The node life-cycle is a logical description of the behaviour of a node and it is often depicted as a state-machine indicating the sequence of tasks performed by the node. There are generally three different types of node behaviour: **Event driven**, **Log driven** and **Hybrid** behaviour.

In an **Event driven** life-cycle, the node will sleep until the occurrence of one or more predefined events. In relation to the previous studies in [HO14], events may for instance be impacts or freezing temperatures. It is often advantageous to use event driven life-cycles when persistent storage or node lifetime are an issue. The drawback of event driven life-cycles is that time based logging is difficult to implement because they typically lack time-synchronization.

In comparison, **Log driven** life-cycles are typically time or task based, making them predictable and useful for logging purposes. In relation to the previous studies in [HO14], it was also shown that some platforms simulates event driven behaviour by using a log driven life-cycle which checks conditions at predefined intervals. The drawback of this approach, and log driven behaviour in general, is that impulse events often are missed.

Hybrid life-cycles are essentially a combination of the event and log driven behaviour where the node sleeps until the occurrence of an event or until a predefined alarm-clock wakes the node to perform time-sensitive tasks. The drawback of the hybrid behaviour is that it both gets the advantages and disadvantages of event and log driven life-cycles. More precisely, it may or may not catch impulse events depending on if it was awakened by the alarm-clock and it may loose synchronization with interval-tasks if it was awakened by events.

4.4.1 Logging Time

All of the general types of node behaviour are cyclic; meaning that they continuously repeats a sequence of tasks. It is therefore often convenient to know the duration it takes to complete each cycle. In this thesis, that duration is defined as the **Logging time**.

In log driven life-cycles, the logging time is typically an integral part of time-synchronizing tasks. More specifically, the resting or sleeping time is often adapted dynamically based on the tasks execution time to thereby ensure time-synchronous measurements. An additional benefit of logging time is that it may be useful when predicting battery lifetime.

In contrast, the event driven behaviour is per definition asynchronous. However, the logging time is still valuable as it describes the frequency between events. Similarly to log driven behaviour, this means that log and execution time may be useful to predict node lifetime.

4.4.2 Typical Structures

With the three general types of node behaviour in mind, it is possible to derive a set of typical node life-cycle structures used in wireless sensor networks. Each of the typical structures can be represented as a sequence of general task or building components which are included depending on the application. Hence, it is possible to derive multiple life-cycles from the typical structures.

4.4.2.1 Polling Node

The polling node structure is log-driven and focused on polling sensor measurements to other nodes in the network. Figure 4.5 illustrates the typical polling node life-cycle.

For simplicity, the details of the individual polling node tasks have been described separately in Figure 4.6.

Considering Figure 4.5 and 4.6 it is noteworthy that the node is allowed to skip the communication step and thereby perform multiple measurements for each message. It is especially in this case where persistent data storage is relevant. A final note is that the polling structure may exchange any kind of data, but not necessarily (or only) sensor measurements.

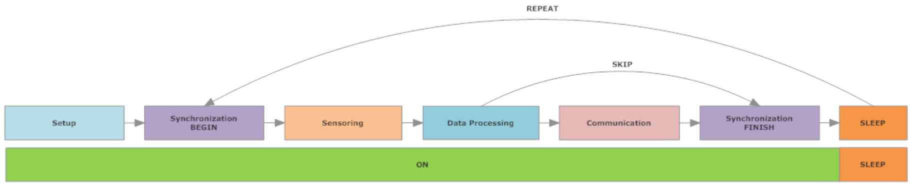


Figure 4.5: Polling node life-cycle

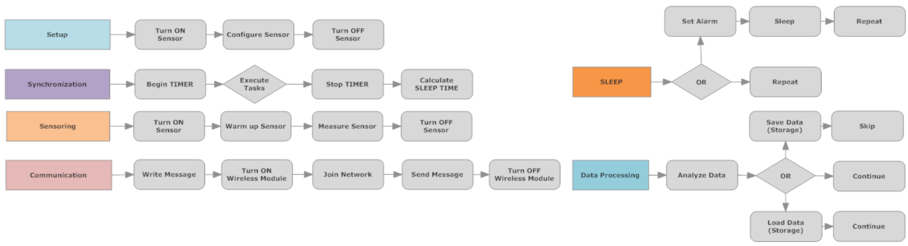


Figure 4.6: Polling node tasks

4.4.2.2 Command-based Node

The command-based node structure is event driven and focused on responding to instructions from other nodes in the network. Figure 4.7 illustrates the typical command node life-cycle.

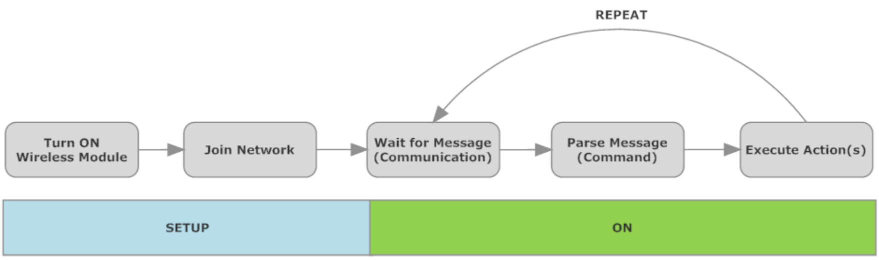


Figure 4.7: Command node life-cycle

Considering Figure 4.7, it is noteworthy that the node does not sleep. This is because the node typically can't predict when commands will arrive. It is theoretically possible when commands can be expected to arrive in intervals, but it is challenging because global time synchronization is difficult in distributed systems. An additional note is that the executed actions may vary depending on the specific case; the node may for instance perform sensor readings or communication as response to the command.

4.4.2.3 Event Node

The event node structure typical for event driven behaviour and is focused on recording or warning the network about events. Figure 4.8 illustrates the typical event node life-cycle.

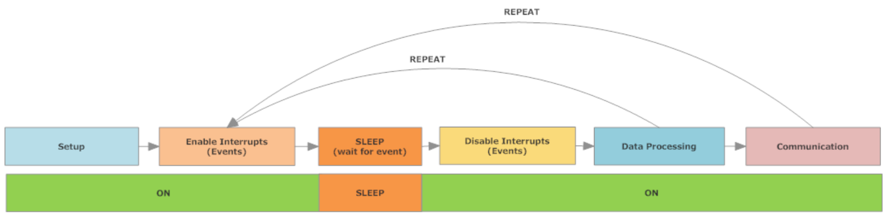


Figure 4.8: Event node life-cycle

For simplicity, the details of the individual event node tasks have been described separately in Figure 4.9.

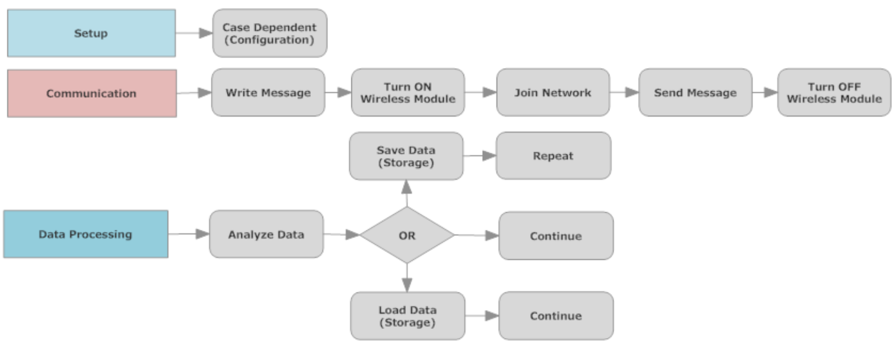


Figure 4.9: Event node tasks

Considering Figure 4.8 and 4.9 it can be seen that event nodes sleep between events, which is contrary to the command node where the node needs to be awake to receive commands. It can therefore be said that event nodes lifetime is dependent upon the event frequency. Additionally, it may be noted that event nodes can respond differently to events depending on the intended application.

4.5 Battery Lifetime and Consumption

Many wireless sensor networks rely on batteries to power nodes, which in turn limits the possible node and system lifetime. This dependency therefore makes battery lifetime a common concern in WSN design.

Basic theory on batteries states that battery lifetime can be estimated through Equation 4.1, given the following information:

Capacity How much power is stored within the battery initially?

Consumption How much power is drained from the battery?

Discharge How does the battery discharge over time?

$$\text{Battery Lifetime} = \frac{\text{Battery Capacity}}{\text{Power Consumption}} \tag{4.1}$$

However, there are various external conditions that may impact battery lifetime - most importantly thermal and ageing conditions. These impacts are hard to estimate and not immediately considered in Equation 4.1. To illustrate how much temperature impacts battery lifetime, Figure 4.10 has been included from the studies in [YSC$^+$12]:

Considering Figure 4.10, it indicates that the performance of Li-Ion batteries may decrease significantly when the temperature drops. In relation to this, it is often possible to find battery discharge graphs from the homepage of the manufacturer; which often assume 25°C. However, most Litium-Ion batteries can be assumed to have an almost linear discharge graph. As a precaution, it may therefore be recommendable to subtract 25-50% from the battery capacity when temperatures below 25°C are expected.

Power consumption of nodes is difficult to estimate in a WSN, because nodes may change between different power states and switch hardware on and off as needed. To make a fairly accurate estimate, it is therefore necessary to describe the power consumption so it reflects the node life-cycle. With the node life-cycle in mind Equation 4.2 thereby estimates the battery consumption of a node.

$$\text{Power Consumption} = \sum_{s=1}^{States} \sum_{p=1}^{Parts} consumption_{sp} \times \frac{t_{sp}}{t_{total}} \tag{4.2}$$

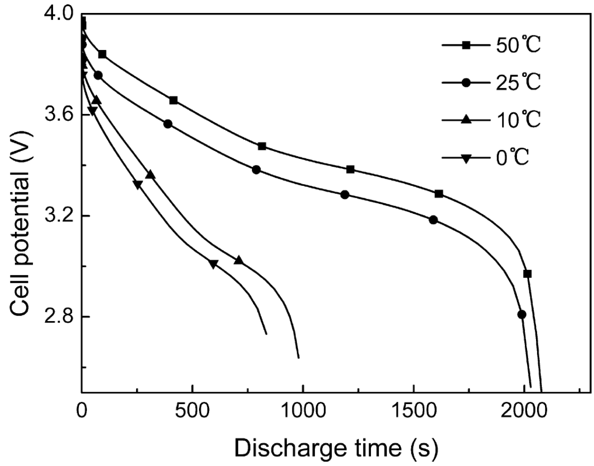


Figure 4.10: (Li-Ion) Influence of temperature on battery 2C discharge performance; originates from [YSC+12]

Given an initial battery capacity and adjusting for temporal conditions, it is therefore theoretically possible to estimate the battery lifetime of a node in a WSN through Equation 4.2 and 4.1.

It is seen that the battery lifetime will always be a problem. Choose between expenses and space for a big battery or expenses for regular replacements and the dilemma between short battery lifetime and longer sensor node sleep time to save battery with the consequence of fewer data and warm-up of sensors may be inadequate. The solution is to apply energy harvesting usually from light or vibration in connection with wireless nodes that may extend the battery lifetime significantly or even act as the main power source with the battery as a backup. However, it is outside the scope of this thesis to go any deeper in this field. It should just be stressed that energy harvesting should be considered for most wireless solutions.

Chapter 5

Performance Evaluation

One of the challenges in WSN design is to estimate the performance of the platform used for implementation and thereby validate the system requirements. To achieve this, the design parameter performance of the *Libelium Waspmote* platform is therefore tested through experiments in the following sections.

5.1 Communication Range and Quality

The connectivity in a wireless network is dependent upon the communication range of the devices used in the network. As mentioned in Section 4.3 signal strength and packet error rates are useful indicators of the connection quality in relation to communication range.

To this end, two experiments were conducted: 1) testing the communication range in an open area 2) testing the indoor communication range within a populated building.

5.1.1 Hardware

During the experiments two different ZigBee modules were used: 1) a module with a 2dBi omnidirectional antenna and 2) a module with an on-chip antenna.

Module	Radio	Frequency	Protocol	Power	Sensitivity	Distance
2 dBi antenna	ZB-Pro	2.4 GHz	ZigBee - Pro	50 mW	-102 dBm	Unlisted
On-chip antenna	ZB-Pro	2.4 GHz	ZigBee - Pro	50 mW	-102 dBm	360 m

Table 5.1: Communication Module Specification[Lib13b][Lib13e]

As seen in Table 5.1 the line-of-sight (LoS) communication range is unspecified in the official documentation. However, the LoS communication range is listed to 7 km for the corresponding module with a 5 dBi antenna.[Lib13b]

5.1.2 Open Area

The open area experiment were performed over a distance of 50 meters with no obstacles. Figure 5.1 illustrates how distance impacts signal strength with the Waspmote platform.

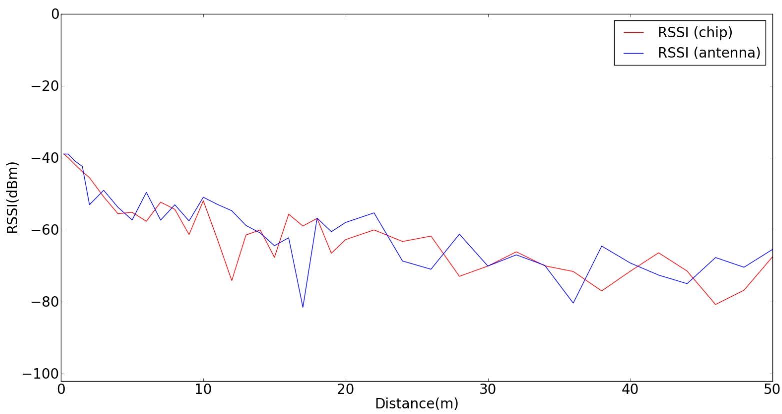


Figure 5.1: RSSI in open area communication with Waspmote

Reflecting on Figure 5.1, it is apparent that signal strength indeed decreases as the distance increases. However, to determine the point at which the connection becomes unreliable, it is necessary to consider the error rate illustrated on Figure 5.2.

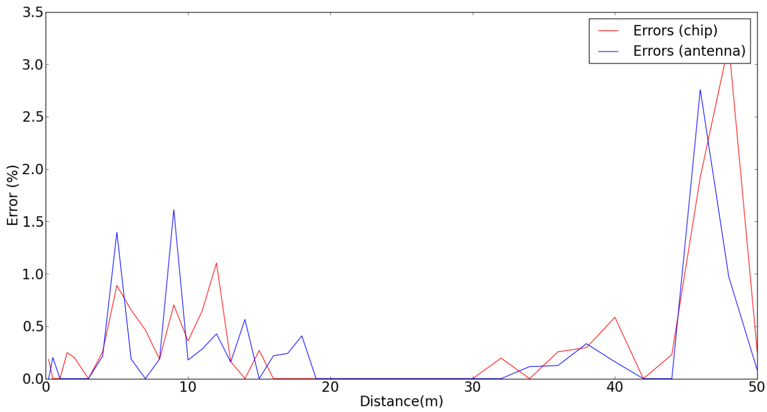


Figure 5.2: Error rate in open area communication with Waspmote

From Figure 5.2 is can be deduced that the error rate is lower than 3.5% throughout the 50 meters, which seems acceptable for most applications. That being said, there is a significant spike around 44 meters where the error rate more than doubles the highest previous value. It may seem a little peculiar that the error rate at short range is higher than at medium range. The explanation is probably that the transmitted radio signal causes interference at the receiver from reflections in the surroundings at certain distances.[Fre]

5.1.3 Indoor Populated Building

The indoor experiment were performed in Building 118 on DTU campus to investigate the communication performance that can be expected in a populated building. Figure 5.3 illustrates the experiment location and the positions at which signal strengths were measured.

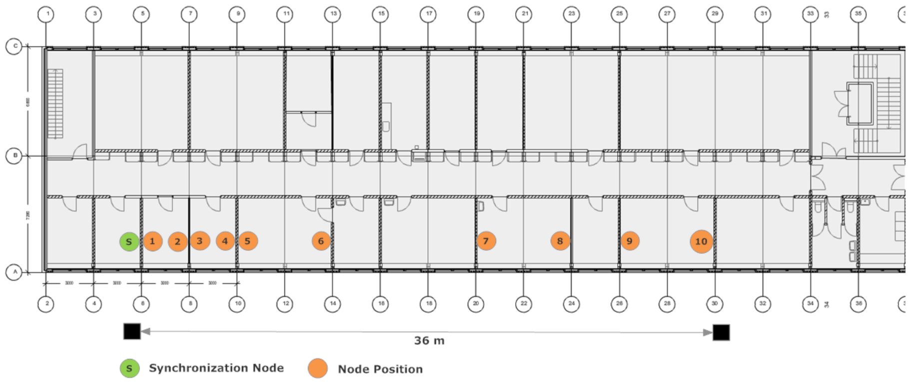


Figure 5.3: Measurement positions in Building 118 (DTU)

As it can be seen from Figure 5.3, signal strengths were measured at ten different positions with up to eight obstructing walls in between. However, being a populated building, additional obstructions such as people and furniture were present during the experiment. Figure 5.4 illustrates how the signal strength progressed at position 1 through 10.

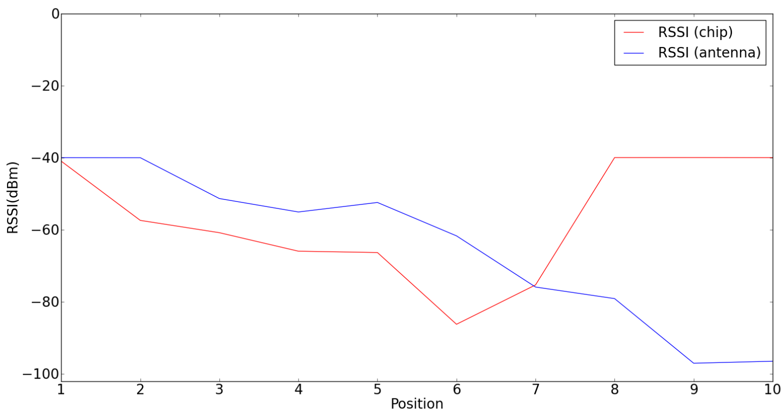


Figure 5.4: RSSI in indoor communication with Waspmote

Reflecting on Figure 5.4 it is apparent that signal strength indeed decreases as the distance and number of obstacles increases. However, to determine the point at which the connection becomes unreliable, it is necessary to consider the error rate illustrated on Figure 5.5.

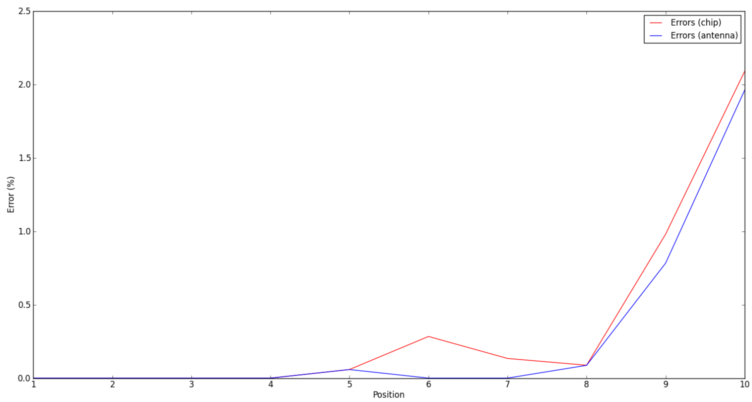


Figure 5.5: Error rate in indoor communication with Waspmote

From Figure 5.5 is can be deduced that the error rate is lower than 2.5% for all the measured positions distributed over 36 meters. That said, the error rate begins to increase significantly around 30 meters.To describe the impact obstructions in a building have on the communication quality, a similar experiment were performed with the aim of testing signal strengths through floors. To this end, Figure 5.6 illustrates how signal strengths progress between the 2^{nd} floor and the basement in Building 118 at DTU. The nodes were placed at the same horizontal position, but three floors apart. Basically, through a concrete construction.

In comparison with the open area experiment, the results indicate that obstructions may interfere with wireless signals. This is especially noticeable when considering the signal strengths, in Figure 5.4, which are lower compared to the open area experiment. That said, considering the error rates, obstructions do not seem to make indoor communication unreliable, but merely reduce the communication range. There were no errors in the communication test through floors; possibly because no objects in the environment caused interference of the radio signal.

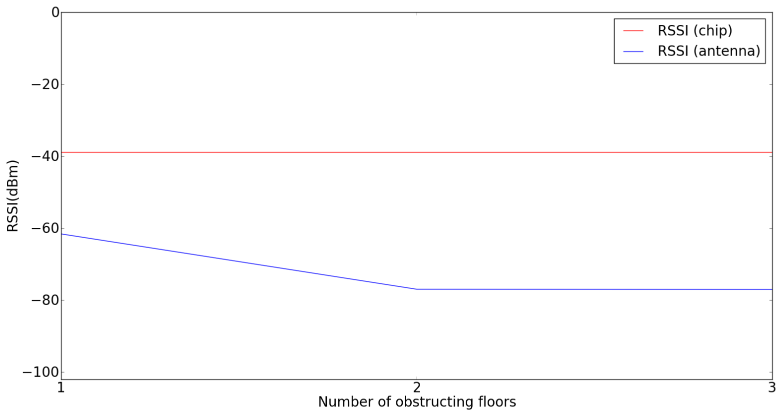


Figure 5.6: RSSI in indoor communication through floors with Waspmote

5.2 Sensor Quality

Reliability and accuracy of sensor measurements are central to the performance of many of the proposed services. In order to determine the sensor quality and accuracy, the sensors were tested at an office, expecting that variation, due to office hours, would be reflected in the results. To make the results comparable, the tests were performed in parallel with a trusted HOBO device, which is commonly used for temperature, humidity and CO_2 measurements at DTU Civil Engineering.

5.2.1 Temperature Sensor

As mentioned in Chapter 1 temperature measuring is important for many aspects of the building process and also in relation to independent commissioning tasks. In order to evaluate the plausibility of each application it is important to validate the accuracy of the sensor.

The MCP9700A sensor is recommended by Libelium for temperature sensing with the Waspmote platform.[Lib13a]

5.2.1.1 Specifications

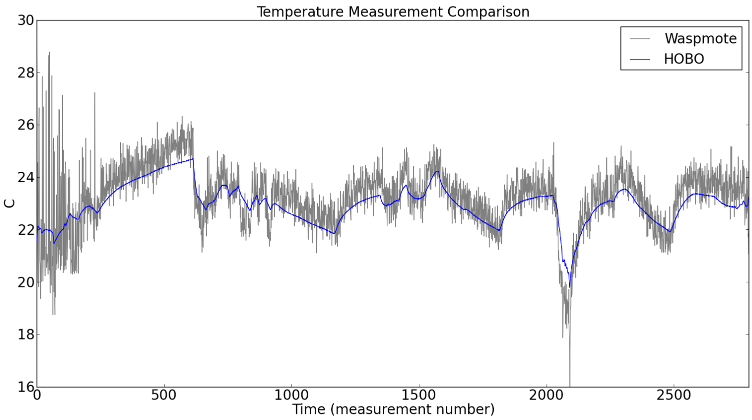
Measurement range	[-40°C ,+125°C]
Output voltage (0°C)	500mV
Sensitivity	10mV/°C
Accuracy	±2°C (range [0°C, +70°C])
Supply voltage	2.3 - 5.5 V
Response time	1.65 seconds (63% response from +30 to +125°C)
Typical consumption	6μA
Maximum consumption	12μA

5.2.1.2 Calibration

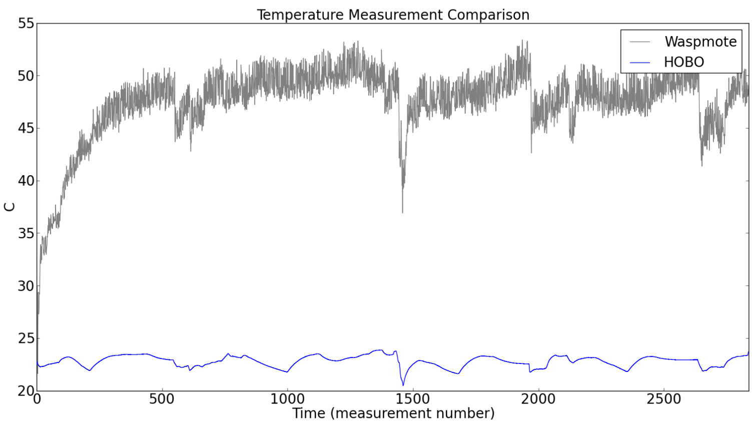
The output from the temperature sensor is automatically converted to celsius degrees through the Waspmote API. The recorded measurements can, however, be scaled up or down by means of programming. The recommended warm up time of the sensor before it can take accurate measurements is 100ms.

5.2.1.3 Results

The temperature measurements performed during two consecutive weeks, measured in degrees Celsius, are illustrated on Figure 5.7.



(a) Week 1



(b) Week 2

Figure 5.7: Temperature measurements

Considering Figure 5.7a there seem to be a larger variation in the results obtained from the *Waspmote* sensor, though they otherwise reflect the pattern observed through the HOBO device. That said, the variation correlates with the sensor specification of $\pm 2^{o}C$, which is determined to be sufficient for most purposes. As it can be derived from Figure 5.7b a scaling problem occurred during the second week of measurements, where the Waspmote sensor was offset by approximately 25°C. However, the Waspmote measurements otherwise reflected the pattern observed through the HOBO device and it was not possible to repeat the observed behaviour in other trials.

5.2.2 Humidity Sensor

As mentioned in Chapter 1 humidity measuring is important to many aspects of the building process and also in relation to independent commissioning tasks. In order to evaluate the plausibility of each use case it is important to validate the accuracy of the sensor.

The 808H5V5 sensor is recommended by Libelium for humidity sensing with the Waspmote platform.[Lib13a]

5.2.2.1 Specifications

Measurement range	0 - 100%RH
Output signal	0.8 - 3.9V (25°C)
Accuracy	<±4%RH (at 25°C, range 30 - 80%), <±6%RH (range 0 - 100)
Supply voltage	5V DC ±5%
Operating temperature	[-40, +85] °C
Response time	<15 seconds
Typical consumption	0.38mA
Maximum consumption	0.5mA

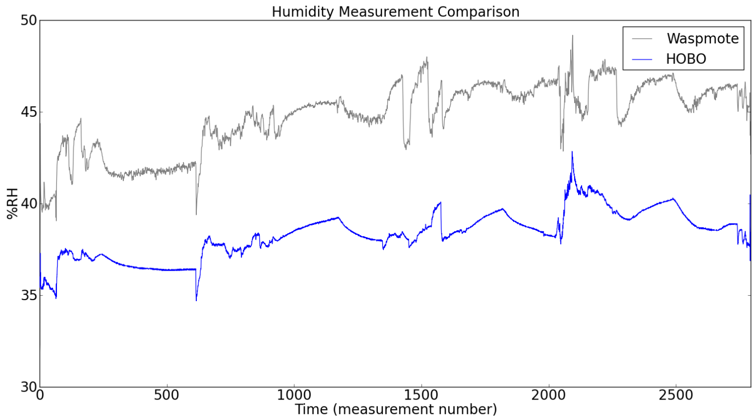
5.2.2.2 Calibration

The output from the 808H5V5 sensor is converted to relative humidity automatically through the Waspmote API. The recorded measurements can, however, be scaled up or down programmatically. The recommended preparation time of the sensor is 15s.

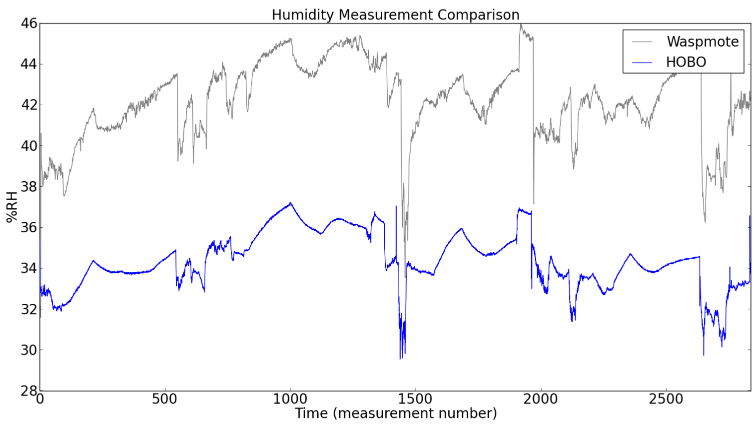
5.2.2.3 Results

The humidity measurements performed during two consecutive weeks, measured in relative humidity (%RH), are illustrated on Figure 5.8.

As it can be seen from Figure 5.8, the humidity results indicate that the Waspmote sensor is offset by 4-5%, but otherwise accurate, in comparison to the HOBO device.



(a) Week 1



(b) Week 2

Figure 5.8: Humidity measurements

5.2.3 CO_2 Sensor

Reliable measurement of gas concentration is very difficult to do and requires careful calibration of the sensors. Furthermore, gas sensors are known to need re-calibration after some time.

The TGS4161 sensor is recommended by Libelium for CO_2 sensing with the Waspmote platform.[Lib13a]

5.2.3.1 Specifications

Measurement range	350 - 10000ppm
Voltage at 350ppm	220 - 490mV
Sensitivity	44 - 72mV (variation between the voltage at 350ppm and at 3500ppm)
Supply voltage	5V ±0.2V DC
Operating temperature	[-10, +50] °C
Response time	1.5 minutes (to 90% accuracy)
Average consumption	50mA

5.2.3.2 Measuring CO_2 Concentration

Before taking measurements, the warm up time of the sensor is must be decided: more time yield more accurate results. The minimum warm up time is 30 s, while a high accuracy measurement requires at least 10 min.

The following equations describe how the voltage measured by the TGS4161 sensor may be converted to gas concentration (ppm).[Libb]

$$deltaemf = \left(baseline - \frac{volt}{gain}\right) \times 1000 \tag{5.1}$$

$$ppm = 10^{\left(\frac{deltaemf + 158.631}{62.877}\right)} \tag{5.2}$$

Where *baseline* represents the voltage at 350 ppm, *gain* represents the calibrated gain of the sensor, and *volt* represents the output voltage of the sensor.

5.2.3.3 Calibration

Calibration of the CO_2-sensor is highly recommended in order to get accurate results. The calibration procedure is as follows[Lib13a][Libb]:

1. Set the GAIN of the sensor to amplify the output voltage to adjust it to the analog-to-digital converter of the Waspmote. A gain of 7-10 is recommended to utilize the full voltage range.
2. If the sensor is new or hasn't been used in a long time, perform a burning procedure on the sensor. This procedure requires that the sensor is kept ON for at least 12 hours.

3. Find the correct voltage under ambient air CO_2 concentration which should be between 220 mV and 490 mV. This value can be found in at least two ways:
   (a) Test the sensor in a gas-chamber where the CO_2 concentration is constantly at a level 350 ppm.
   (b) Test the sensor in parallel with another calibrated sensor and calibrate it accordingly.

5.2.3.4 Results

The CO_2 measurements performed during the sensor burning procedure were collected, and illustrated in Figure 5.9, in attempt to learn the significance of the procedure.

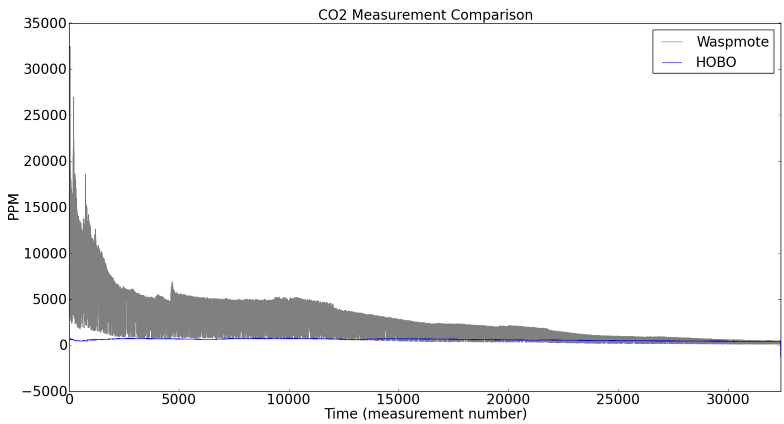


Figure 5.9: CO_2 measurements from the burning procedure

As it can be derived from Figure 5.9, the recorded CO_2 values from the first three days of measurements reached unrealistic proportions. However, they slowly stabilized at a realistic concentration level. This suggests that it is prudent to use burning procedures that are significantly longer than the 12 hour minimum. In comparison, Figure 5.10 illustrates the results obtained in the week after calibration.

Considering Figure 5.10, it is clear that the recorded CO_2 values clearly reflect the pattern observed with the HOBO device. However, there are a lot of variation in the recorded CO_2 values. To mitigate this issue, an average of multiple

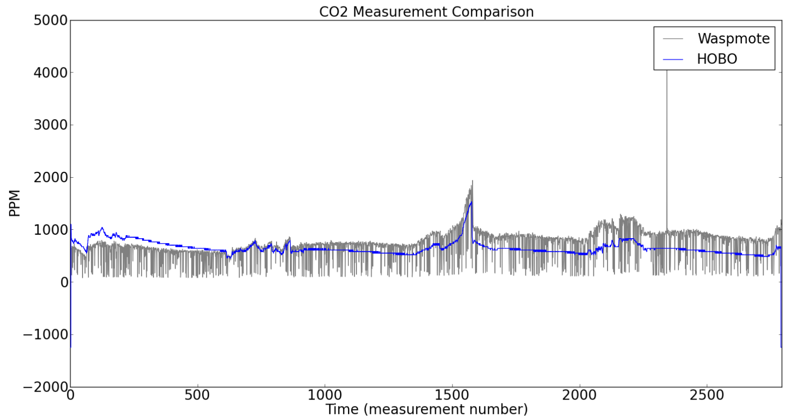


Figure 5.10: CO_2 measurements after calibration

voltage evaluations on the sensor was recorded in the following week - yielding the results in Figure 5.11.

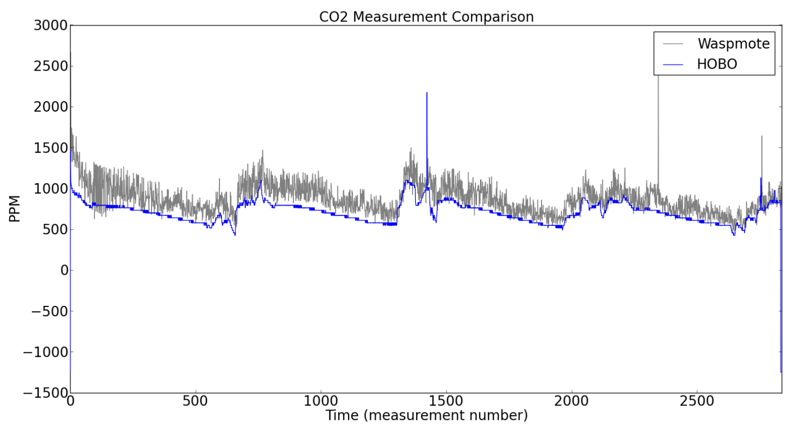


Figure 5.11: CO_2 measurements with multiple voltage evaluations

By comparing Figure 5.10 and 5.11 it can be seen that both clearly reflect the pattern observed by the HOBO device, but that the variation in CO_2 measurements are much smaller on Figure 5.11. It was thus concluded that performing multiple evaluations on the CO_2 sensor in each cycle will improve sensor accuracy a bit. Reflecting back on the results obtained after calibration (Figure 5.10), it was discovered that the highest recorded concentration value tends to be correct. With this in mind, it was then possible to achieve the results illustrated in Figure 5.12, by always selecting the highest concentration value recorded within the last ten measurements.

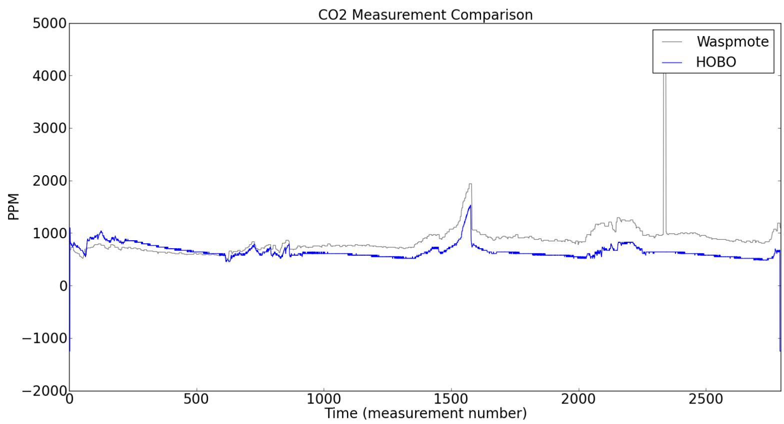


Figure 5.12: CO_2 measurements after calibration filtered by highest ppm within 10 readings

Considering Figure 5.12 it is strikingly obvious that selecting the highest concentration value is a far better strategy than using an averaged value. However, this strategy should be used with cation as the highest concentration level might be an outlier, which reflect unrealistic concentration levels. In conclusion it was determined that the CO_2 sensor is capable of delivering a good performance, but that some measurements generally are misleading. The deviating readings may possibly be a result of electronic noise from the sensor board and the Waspmote board disturbing the analogue to digital conversion of the signal.

5.2.4 Discussion

In terms of sensor quality, it was experienced that two out of three humidity sensors were defect suggesting either poor quality of the device in general or incredibly bad quality control from the manufacturer. That said, the humidity sensor otherwise appears to provide reliable results. It is speculated that the observed humidity scaling difference might be caused by the fact that the sensor operates in the [0.8V (0%) ; 3.9V (100%)] range, whereas Waspmotes use a range of [0.0V (0%); 3.3V (100%)]. The sensor board and Waspmote API is supposed to account for this difference, since the API currently is responsible for the conversion from voltage to relative humidity. The temperature sensor results were within the specified tolerance of the sensor. Except for the measurements collected in Week 2 (Figure 5.7b), that was possibly erroneous, since it was not possible to repeat the observed problem. It is therefore difficult to determine the cause, but it was most likely a loose connection between the temperature sensor and sensor board from moving or handling the node. As a precaution it would therefore be prudent to check the connectivity between the sensor and sensor board before any future experiments. An alternative solution would be to check if the first measurements in any new experiment are probable before leaving the setup. Considering the CO_2 sensor it was discovered that it has a tendency to read measurements which are below the actual gas concentration. As a solution it was found that performing multiple measurements and either selecting the highest measured concentration or and an average will increase the sensor accuracy. In conclusion it was determined that the CO_2 sensor is capable of delivering a good performance, but that some measurements generally are misleading.

5.3 Battery Lifetime

As mentioned in Section 4.5 it is important to know the *Capacity*, *Consumption* and *Discharge* of the battery to estimate battery lifetime.

During the experiments two different rechargeable batteries were used with an initial capacity of 2300mAh and 6600mAh respectively. As part of the *Waspmote* platform, it is possible to measure the current battery voltage in applications which thereby enabled tracking of the battery capacity during the performed experiments.

In terms of discharge, Figure 5.13 illustrates the typical discharge curve of the used batteries.[Lib13e]

As it can be seen from Figure 5.13, the typical discharge curve is fairly consistent with linear discharge as expected of Li-Ion batteries.

5.3.1 Simple Logging Node

The initial battery lifetime experiments were based upon the simple node lifecycle illustrated in Figure 5.14.

In order to estimate the battery lifetime, it was first necessary to describe the

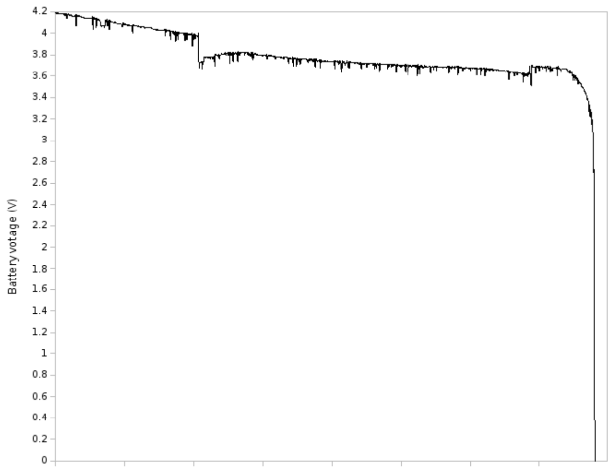


Figure 5.13: Typical discharge curve for battery[Lib13e]

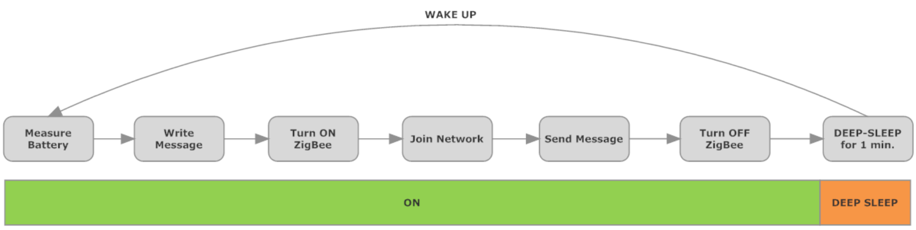


Figure 5.14: Battery application life-cycle

power consumption of the node life-cycle in accordance with Equation 4.2. To do so, the time spent on each task were estimated and cross-referenced with the official power consumption estimates for the active hardware components (See Table 5.2).

By using Equation 4.2 with the data in Table 5.2, the power consumption of the node life-cycle was hereby estimated to $\approx 4.199mA$. Through the use of Equation 4.1 the battery lifetime listed in Table 5.3 was predicted.

5.3.1.1 Results

Figure 5.15 illustrates the discharge curve recorded during the experiment with a 2300 mAh battery. The voltage readings are taken by the standard battery

Part (On)	Power Consumption	Time
Waspmote	15mA	4.3s
ZigBee PRO	45.65mA	4.2s
ZigBee PRO (sending)	105mA	0.1s
Total Power Consumption (ON)	88.04mA	4.3s
Part (Deep Sleep)	Power Consumption	Time
Waspmote	0.055mA	60s
ZigBee PRO (off)	0.000mA	60s
Total Power Consumption (Deep Sleep)	0.055mA	60s

Table 5.2: Power Consumption and Time

Battery Capacity	Expected Lifetime
2300 mAh	547.68 hours $\approx$ 22.82 days
6600 mAh	1571.60 hours $\approx$ 65.48 days

Table 5.3: Expected battery lifetimes

monitoring utility in the Waspmote hardware with limited resolution (digital steps).

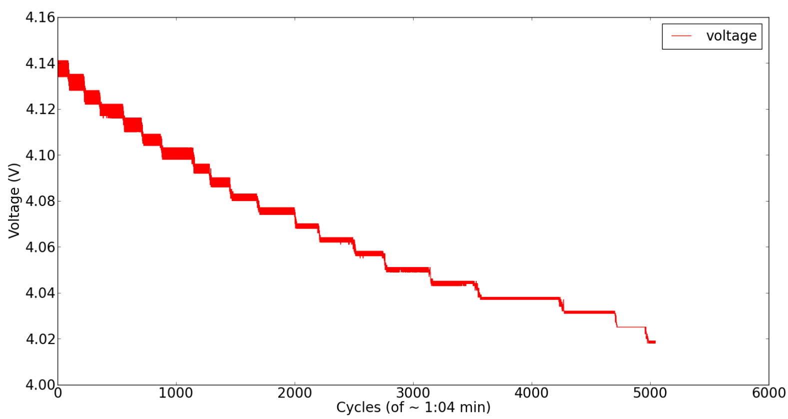


Figure 5.15: Battery discharge curve from Experiment

Based on the results, it was derived that the node life-cycle discharges 1% of the battery capacity in approximately 5.3 hours. Assuming linear discharge the experiment lifetime is therefore estimated in Equation 5.3.

$$\text{Battery Life} = 5,3 \text{ hours} * 100 = 530 \text{ hours} \approx 22,08 \text{ days} \tag{5.3}$$

In conclusion, the predicted battery lifetime is fairly close to the one found in the experiment. It was only offset by 3.25%. Considering the results, it seems like a plausible margin of error especially when environmental conditions such as temperatures are taken into account.[YSC+12]

Chapter 6

Generic Model

The generic wireless sensor network model for the building industry relies on the design parameters introduced in Chapter 4.

6.1 Step 1: Network & Communication

In order to make the model easily usable, a short-cut is provided in Table 6.1, which illustrates the most suitable network topology and communication protocol for each stage in the building process.

After using Table 6.1, it may be helpful to consider Table 4.5 and 4.7 to check if the given application may benefit from unique features associated with one of the appropriate alternatives.

6.2 Step 2: Requirements & Node Life-cycle

Once the desired network topology and communication protocol is identified, the following system requirements must be specified in order to customize the

Stage	Daisy-Chain	Star	Tree	Mesh
Prefabrication	802.15.4 ZigBee	802.15.4 ZigBee	ZigBee	DigiMesh
Transportation	Bluetooth ZigBee	Bluetooth ZigBee	ZigBee	DigiMesh
Construction	Bluetooth 802.15.4 ZigBee	Bluetooth 802.15.4 ZigBee	ZigBee	DigiMesh
Commissioning	Bluetooth 802.15.4 ZigBee	Bluetooth 802.15.4 ZigBee	ZigBee	DigiMesh
Operation	802.15.4 ZigBee	802.15.4 ZigBee	ZigBee	DigiMesh
Renovation and refurnishing	802.15.4 ZigBee	802.15.4 ZigBee	ZigBee	DigiMesh
Dismounting	Bluetooth Wi-Fi	Bluetooth Wi-Fi	ZigBee	DigiMesh

Table 6.1: Network topologies and communication technology in building process stages (red = unwanted, yellow = valid alternative, green = preferred choice)

resulting WSN appropriately:

Expected lifetime What is the expected lifetime of the system? And how often (if ever) is it acceptable to change or recharge batteries ?

Logging time How often should sensor measurements be taken and sent to the synchronization node?

Sensor Accuracy What accuracy is required of the sensor?

These requirements are central to the design of node life-cycles, because the lifetime is influenced by the logging time and sensor accuracy sets a lower bound on the logging time due to sensor warm up.

With this in mind, design a node life-cycle that suits your application needs. To simplify node life-cycle design the typical structures and tasks listed in Section 4.4 may be used for reference.

6.3 Step 3: Validation of Logging time

After construction of the node life-cycle, estimate how much time a node will spend on each task and in each state. As early validation verify that the tasks estimated time does not exceed the required logging time. Appendix A lists rough time estimates for typical tasks performed with the Libelium Waspmote Platform.

6.4 Step 4: Validation of Expected Lifetime

Use the individual task time and power consumption estimates to determine the expected node lifetime (see Equation 4.2 and 4.1). Compare the resulting lifetime prediction to the requirements to validate the feasibility of the system. If the system is infeasible, consider the option of larger battery capacity, energy harvesting, direct power supply and extending sleeping time of nodes that allow this. Appendix B lists the official power consumption estimates with the Libelium Waspmote Platform.

6.5 Step 5: Planning the Physical Setup

Having validated the system requirements, the final step is to plan the physical setup. In principle, the purpose is to ensure sufficient network connectivity within the system. A subsequent goal therefore is to select wireless module(s) with enough range to connect nodes within the network.

To plan the physical setup, it is often helpful to make a scaled drawing of the location indicating placement of sensors. This way, all nodes with restricted or predetermined positions can be placed first. Considering the placement of nodes, it is then important to determine the distance of the longest link between nodes that should be able to communicate with or through each other. This distance reflects the minimal communication range required of the wireless modules. Depending on the applied network topology and communication protocol, it may be possible to add intermediary routing nodes and thereby reduce the communication range requirement. However, in systems where all nodes are mobile and relies on the mesh topology to connect the network, planning may be done differently. In such cases, determination of the required communication range depends both on the size of the area and how nodes are expected to cluster.

6.6 Discussion

Considering Table 6.1, it is obvious that the Daisy Chain topology generally is not recommended. However, there are cases where it makes sense to consider it; for instance in temporary setups or when limited functionality is required and when installation costs should be reduced as much as possible. Another point to mention is that the Radio-frequency identification (RFID) has not been included. This is mainly because it generally is not associated with wireless sensor networks, though arguments definitely can be made for using it for cheap identification purposes. It is for instance a relevant, non-WSN alternative in the transport and demolition phases.

By considering the building process as a whole, it is apparent that the tree topology offers the best overall performance. That said, depending on the application, it may be preferable to prioritize some phases higher than others. It is also shown from Figure 6.1 that the mesh topology has great potential in a mobile context, although it lacks an open protocol which is supported by third party devices.

In relation to communication protocols it can be deduced from Table 6.1 that the most recommended protocol throughout the building process is ZigBee. This is mainly attributed to good support from third party devices and its use of the tree topology, which either is preferred or a reasonable alternative in all the phases of the building process. In comparison, Bluetooth provides some intriguing possibilities from integration with portable devices and vehicles, but is limited by a short communication range and a low scalability.

6.6.1 Multi-phase systems

Table 6.1 is focused on optimal design for the individual phases of the building process. To design systems targeting multiple phases of the building process, it is therefore necessary to find the optimal compromise. It should be possible to get ideas for optimal solutions by considering the phases simultaneously in Table 6.1. That being said, it is recommendable to consider the respective advantages and disadvantages by consulting Chapter 4 (or at least Table 4.5 through 4.7), since the best compromise may be application dependent. In this, it may be considered that some communication types support multiple network topologies and that nodes can be equipped with multiple different communication modules if necessary. In relation to the Waspmote platform, such functionality could be achieved by using the Extension Radio Board.[Lib13e]

6.6.2 Prefabrication

In the prefabrication phase of the building process, a WSN might for instance be used to monitor temperature and moisture levels during the drying process of concrete elements. As indicated in Table 6.1, the tree topology with ZigBee communication is suggested for such tasks. The reasoning is that the monitoring locations are fairly static; making it easy to guarantee coverage through tactical placement of router nodes. As an additional benefit, this solution yields increased sensor node lifetime compared to the mesh topology. However, both the star and mesh topologies might be relevant under certain conditions. For instance, in case the prefabrication site is small, the star topology might be sufficient. One of the strongest arguments for using the ZigBee protocol in the prefabrication phase is that it offers integration with many industrial systems.

6.6.3 Transportation

The transportation phase is in essence a transition between the prefabrication phase and the construction phase where prefabricated components are transported to the building site. It is therefore reasonable to consider if the WSN should target multiple phases. As previously mentioned, Table 6.1 is focused on optimal design for the individual phases and refer to Section 6.6.1 for multiphase systems. Assuming the transportation phase is targeted individually, it is tempting to use the Star topology in combination with Bluetooth communication. Hereby, the system could offer easy wireless interaction with mobile devices such as phones, tablets and PCs, which would provide the driver with live updates on and warnings about the cargo-status. The drawback of using Bluetooth communication is its limited communication range, which likely would require installation of an intermediary forwarding device on trucks. Consequently, it may even be a show-stopper since transport companies may be unwilling to make the necessary investments. The preferable solution would therefore be to use event-based ZigBee nodes which record occurrences of unwanted conditions and compile transport-reports upon arrival. Considering Table 6.1 ZigBee communication would also be well suited as a transition between the *Prefabrication* and *Construction* phase.

6.6.4 Construction

The construction phase involves a lot of movement where building components arrive, are stored and assembled at the building site. It is therefore important that the resulting WSN functions in a mobile context and is capable of determining proximity. The mesh topology is well suited for such purposes for two reasons; 1) it is good when nodes are mobile and 2) all nodes can talk directly to each other and thereby detect proximity. The main drawback regards protocol availability, which makes it difficult to integrate the system with third party devices. The DigiMesh protocol is a good example, as it applies the mesh topology and it makes it possible to wake nodes when a message is received, but lacks third-party support. For many applications, the tree topology would also make sense as tactical placement of router nodes can be used to ensure full coverage. This especially makes sense if combined with ZigBee communication, which is widely supported by third party devices. That said, assuming the ZigBee nodes utilize sleeping states, it would make proximity determination much harder as it would require nodes to be awake at exactly the same time. The main reason why the star topology has not been mentioned as an alternate for this phase is because of range-concerns. Put simply, in many cases the synchronization node properly won't be powerful enough to ensure full coverage at the building-site. However, it may be noted that given a small construction-site the star topology could be sufficient.

6.6.5 Commissioning

Similarly to construction is the commissioning phase - a mobile setting where proximity may be utilized to prevent or detect errors early. For this reason the same arguments apply as in the construction phase.

6.6.6 Operation

In the operation phase, a WSN might be used as a monitoring and control system to optimize the indoor climate and resource-efficiency of a building. As seen from Table 6.1 it is preferred to use ZigBee for communication. There are several good arguments for this: firstly, that ZigBee is an open standard which makes it easy to integrate with third-party devices and systems and secondly, because ZigBee communication has a good range and security features while supporting the preferable network topologies for static environments. The tree topology is suggested for networks in the operation phase. This is because it is easy to extend, manage and maintain while it is simple to place routers tactically around the building to ensure coverage. That being said, it may be sufficient to use the Star topology in small buildings where it is feasible to reach all nodes from the synchronization node. In contrast, mesh networks are unwanted because there only exist few available protocols, where most are proprietary and therefore are unable to integrate properly with third-party devices.

6.6.7 Renovation and refurnishing

There are essentially two ways to consider WSNs in relation to renovations: 1) as a tool to ease the renovation process and 2) as retrofits, possibly to optimize resource-efficiency. For the first interpretation, recommendations would correlate with those of the construction phase; whereas the latter would correlate with the operation phase. Table 6.1 is focused on the later, since there are great potential in optimizing the resource-efficiency of existing buildings to generate operational savings.

6.6.8 Dismounting

In the dismounting phase WSNs would most likely be focused on component identification and disposal applications. As such, it would be preferable to use Bluetooth or Wi-Fi communication because it enables easy interaction with mobile devices used by workers on-site. That being said, depending on the application the scalability of the network must be considered, where especially Bluetooth might cause problems. In terms of network topology it is preferred to avoid hop communication, since nodes may be removed at any time breaking or crippling the network. However, as long as devices supporting the given communication are available to the workers most communication protocols would properly work. Hence, open standards like ZigBee would be decent alternatives, whereas proprietary protocols like DigiMesh might be problematic.

Chapter 7

Case: Greenland

As mentioned in Chapter 3, the case study of this project has been decided to be the Apisseq dormitory in Sisimiut (Greenland). By using the generic model, it is hereby investigated how the WSN technology can help solving the over-ventilation problem of the building as retrofit as a comparison to the standard (wired) solution.

7.1 The Building

The Apisseq dormitory is an energy efficient building, built in 2010. The building is intended to be a testing site for modern technologies, not commonly used in the Arctic, to reduce energy consumption while improving indoor environment quality. The Technical University of Denmark (DTU) therefore donated a monitoring system that can measure energy consumption, indoor air quality and moisture in the building.[VK10][KHO14] In 2012, it was shown that the dormitory constantly is over-ventilated, due to a poorly designed ventilation system, and consequently dramatically increases the heat and electricity consumption.[KR12]

7.1.1 Layout

The shape of the building is circular and it consists of three floors: basement, ground floor and first floor. The basement contains storage space, laundry, and two ventilation rooms, whereas the ground and first floor are mainly dedicated to flats and common rooms as indicated on Figure 7.1.

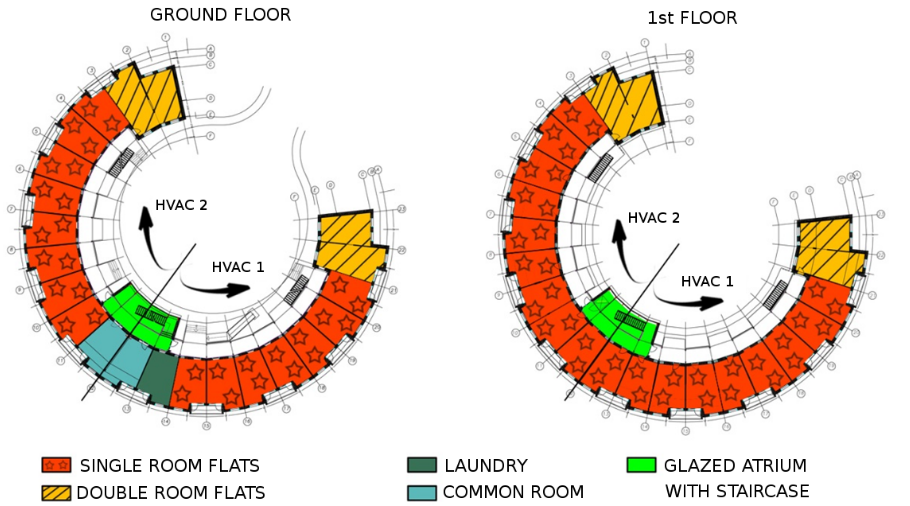


Figure 7.1: Ground and First floor of the Apisseq dormitory[VK10][KHO14]

As indicated on Figure 7.1 there are a total of 33 single and 4 double flats in the dormitory. Additionally, there are two ventilation units, located in the basement, which each services exactly half of the dormitory.[KHO14]

7.1.2 Ventilation System

The ventilation system consists of two identical heating, ventilation and air conditioning (HVAC) units located at opposite ends of the basement. The HVAC units controls the air flow in accordance with Figure 7.2.

As indicated on Figure 7.2, the HVAC units have two fans that vent air in and out the building, respectively. To improve energy efficiency, a heat exchanger is applied between the incoming and outgoing air. The problem is that the fans are too powerful for the building, resulting in over-ventilation. Normally, this would easily be solved by reducing the fan speed and thereby the air-intake, but in the

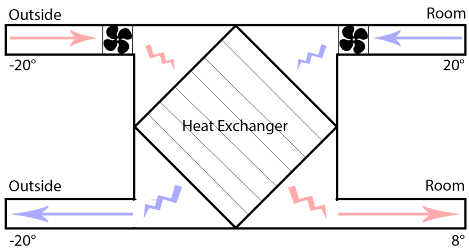


Figure 7.2: HVAC unit design

case of Apisseq even the lowest possible fan speed of 10% is too powerful. It was therefore suggested to install dampers to dynamically regulate the air flow in the building based on CO_2 concentrations and thereby increase the indoor air quality (IAQ) and resource-efficiency. Ideally, a damper would be installed for each room providing an individual and optimal indoor air quality (IAQ) on room level. However, this was deemed economically infeasible. Instead the air flow should be regulated at a HVAC unit level, as indicated on Figure 7.3.

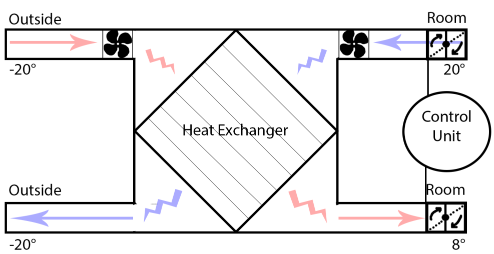


Figure 7.3: HVAC unit with dampers

Regulating the air flow on a HVAC level will result in equal ventilation of the flats connected to the HVAC unit. It is therefore important to regulate the ventilation without compromising the IAQ in any of the rooms. Consequently, it is required to determine the optimal control algorithm 'in situ'.

7.1.3 Prerequisites

Installation of the proposed ventilation control system requires the presence of CO_2 sensors in the flats and need to be installed as retrofits. Additionally, installation of a control unit that may regulate the air flow without compromising the IAQ is required.

7.2 Experimental setup

Given the building layout it is possible to design the experimental setup as a comparative study targeting exactly half of the building. Hence, it will be possible to evaluate the performance of the resulting system before investing in a full scaled setup. The experimental setup should therefore initially target the rooms connected to HVAC 1 (See Figure 7.1), but be scalable to fit the entire building.

7.2.1 Ventilation Integration

Before the ventilation control system can be designed, it has to be considered how the ventilation dampers might be controlled by the system. In this case the damper actuators or more precisely here the Belimo spring-return actuators can be controlled by at voltage signal from 0 to 10 VDC. The Waspmote-platform offers the possibility to output an analogue signal for control by using PWM (Pulse Width Modulation) with which an analog signal can be "simulated" from 0V (0%) to 3.3V (100%). The resolution is 8bit, so up to 255 values between 0-100% can be configured. An additional amplifier is required to condition the control signal for the actuator voltage range. In this way the actuators are directly integrated in the WSN like any other node. Generally, the PWM output signal can be used for "wireless" control in a lot of applications with a proper conditioning amplifier.

7.2.2 Using the Generic Model

In order to design a WSN capable of solving the over-ventilation problem at Apisseq, the generic model is applied to the case.

7.2.2.1 Step 1: Network & Communication

Since Apisseq dormitory is in operation, the WSN control system will be installed as a retrofit. Hence, it can be concluded from Table 6.1, that the resulting system should use the Tree topology with ZigBee communication.

7.2.2.2 Step 2: Requirements & Node Life-cycle

Through consultation with Ph.D. student Martin Kotol from the Apisseq project, the requirements of the system were specified to be:

Expected lifetime of at least one year without battery change.

Logging time of at least every 5 minutes, preferably more often. A logging time of 2 minutes was chosen for the investigation.

Sensor accuracy similar to the results in Section 5.2.3.

In relation to the resulting system, the logging time describes the frequency at which CO_2 measurements are taken. As previously mentioned, these measurements are the foundation of the air-flow control algorithm(s). The logging time requirement therefore reflects the required frequency between air-flow adjustments.

Considering the suggested solution for the ventilation problem, it is concluded that at least two different node behaviours are required: 1) sensor nodes which collects CO_2 measurements in the flats and 2) a control node that regulates the air flow by adjusting the damper position.

By consulting the typical life-cycle structures in Section 4.4 it was deduced that the control node behaviour may be achieved through the *Command node* structure, whereas the sensor node behaviour corresponds to the *Polling node* structure. To specify the required tasks, the resulting life-cycles are illustrated in Figure 7.4 through 7.6.

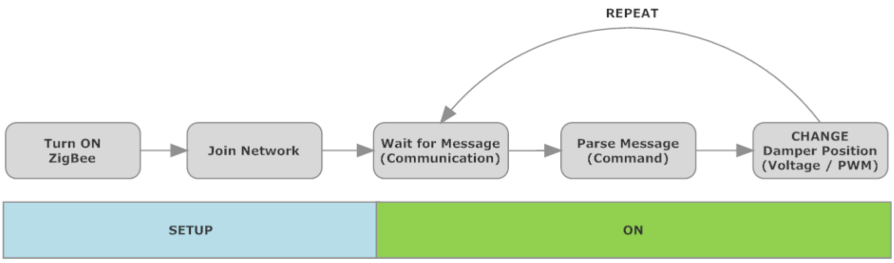


Figure 7.4: Control node life-cycle

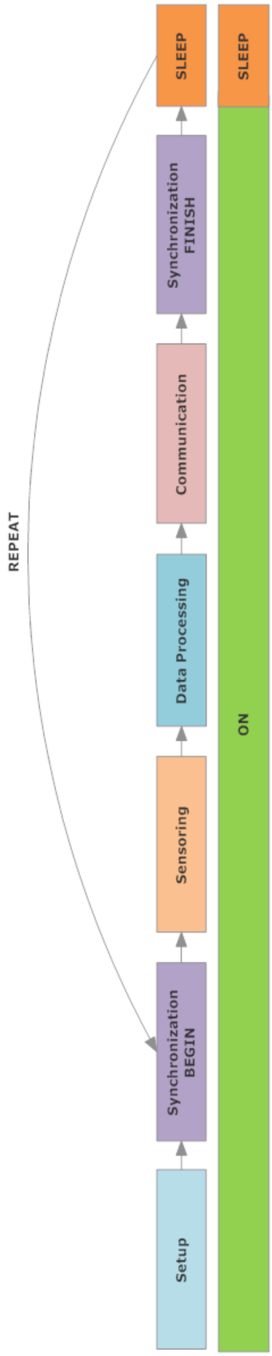


Figure 7.5: Sensor node life-cycle

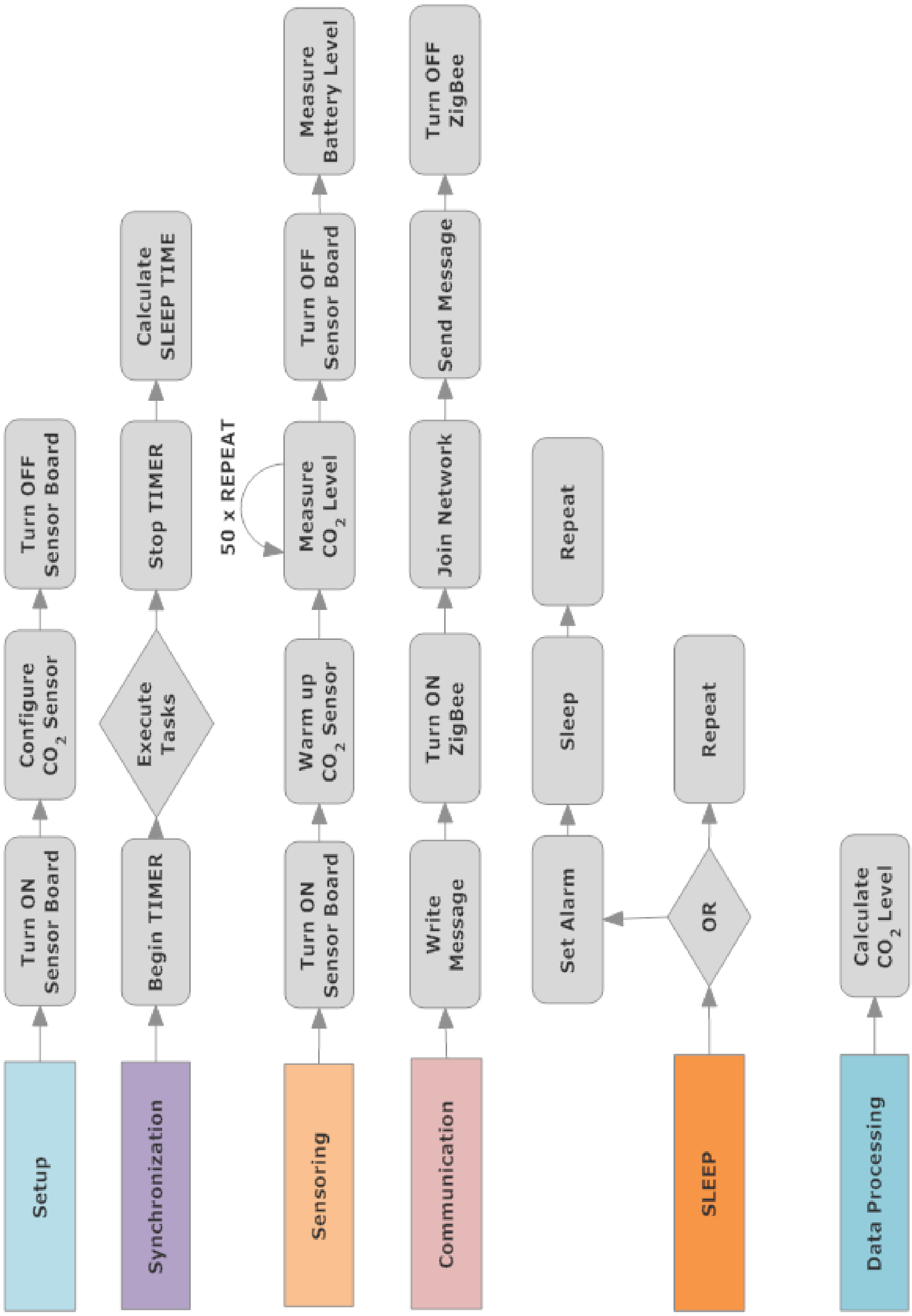


Figure 7.6: Sensor node tasks

7.2.2.3 Step 3: Validation of Logging time

To validate the logging time, the estimates from Appendix A was used to derive node execution time. The control node execution time was evaluated to be approximately $0.3s$ excluding waiting time for messages to arrive. In contrast, the sensor node execution time was evaluated to approximately $64.5s$ (See Equation 7.1).

$$\begin{aligned}\text{Execution Time} &= \text{Sensor Reading} + \text{Data Processing} + \text{Communication} + \text{Synchronization} \\ &= 60.2s + 0.1s + 4.2s + 0.001s = 64.5s \qquad (7.1)\end{aligned}$$

Considering Equation 7.1, it may be noticed that sensor reading is the most time consuming task. This is because the CO_2 sensor requires a long warm up time to ensure accurate measurements.

By comparing the estimated execution times, it can be concluded that none of the node life-cycles exceed the logging time requirements that was chosen to be 120 s. The sensor node is then able to sleep for approximately $55.5s$ in each cycle without breaking the requirement.

7.2.2.4 Step 4: Validation of Expected Lifetime

In order to estimate the expected battery lifetime, it is first necessary to describe the power consumption in accordance with Equation 4.2. To do so, the time spent on each task was cross-referenced with the official power consumption estimates for the active hardware components (See Table 7.1 and 7.2).

Part (On)	**Power Consumption**	**Time**
Waspmote	15mA	64.5s
ZigBee PRO	45.65mA	4.2s
ZigBee PRO (sending)	105mA	0.1s
Sensor Board (CO2)	52mA	60.2s
Total Power Consumption (ON)	66.67mA	64.5s
Part (Deep Sleep)	**Power Consumption**	**Time**
Waspmote	0.055mA	55.5s
ZigBee PRO (off)	0.000mA	55.5s
Sensor Board (off)	0.000mA	55.5s
Total Power Consumption (Deep Sleep)	0.055mA	55.5s

Table 7.1: Sensor Node: Power Consumption and Time

By using Equation 4.2 with the data in Table 7.1, the power consumption of the sensor node life-cycle is estimated to be approximately $35.86mA$. In comparison, the power consumption of the control node life-cycle is approximately $60.73mA$, which is a consequence of not using a sleep-state to conserve power.

Part (On)	Power Consumption	Time
Waspmote	15mA	120s
ZigBee PRO	45.65mA	120s
ZigBee PRO (receiving)	50.46mA	0.2s
Total Power Consumption (ON)	60.73mA	120s

Table 7.2: Control Node: Power Consumption and Time

Given the power consumption of each node it is possible determine the expected battery lifetime through Equation 4.1.

Sensor Node	
Battery Capacity	**Expected Lifetime**
2300 mAh	64.14 hours ≈ 2.67 days
6600 mAh	184.05 hours ≈ 7.67 days
Control Node	
Battery Capacity	**Expected Lifetime**
2300 mAh	37.87 hours ≈ 1.58 days
6600 mAh	108.67 hours ≈ 4.53 days

Table 7.3: Expected battery lifetime of nodes

Considering Table 7.3, it is clearly infeasible to achieve the required lifetime with battery powered nodes. It is obviously impossible to increase the sleeping time enough without compromising the IAQ. Consequently, the option of energy harvesting or direct power supply must be considered. One easy applicable way to extend battery lifetime is to add a small solar panel that even indoors may deliver enough power from daylight or lamps to charge the battery when the node is sleeping.[Pat] After consultation with Ph.D. student Martin Kotol, it was deemed most appropriate to connect nodes directly to a power-outlet at the Apisseq dormitory. The reasoning was two-fold: 1) it can be hard to predict the performance of energy harvesting because it is often case- and location-dependent 2) it would be easy to connect nodes to a power-outlet within the dormitory.

Now with the external power supply the logging time can be reconsidered. The external power of the battery charging is 100mA at 5V or 0.5W. Assuming a power loss of, say, 10% for charging we get a power of 0.45W. The sensor node consume in average 66.67mA executing and 0.055mA sleeping at nominal 3.7V or 0.25W and 0.0002W, respectively. It can then be concluded that the node does not need to sleep at all since the effective charging power is higher than the average consumed power when executing. Being content with a logging time every 120 seconds, the excess power could be used for improving the sensor accuracy by increasing the warm-up time and reducing the sleep time. The dominating factor in the execution time is actually the sensor warm-up time. The maximum permissible power consumption and time during execution can be estimated from the energy consideration in Equation 7.2 using the consumptions given in Table 7.1:

$$Pcharge * (Texc + Tsleep) \geq Pexc * Texc + Psleep * Tsleep \tag{7.2}$$

Texc: execution time
Tsleep: sleeping time
(Texc + Tsleep): logging time
Pcharge: effective power (W) of battery charging
Pexc: average power (W) consumed during execution
Psleep: average power (W) consumed during sleeping

In the general case it may be considered which components in the nodes that should sleep to comply with the maximum permissible power consumption.

7.2.2.5 Step 5: Planning the Physical Setup

In the case of the Apisseq dormitory, where all nodes are static, it is fairly easy to plan the physical setup. Since sensor and control node positions are predetermined, these are placed first. Once the sensor and control nodes are in place, the synchronization node is placed as centrally as possible to minimize the required communication range. This yields the setup illustrated on Figure 7.7 through 7.9.

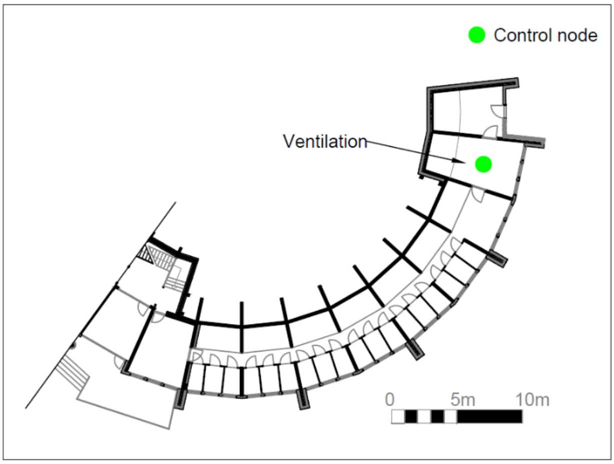


Figure 7.7: Basement: suggested setup

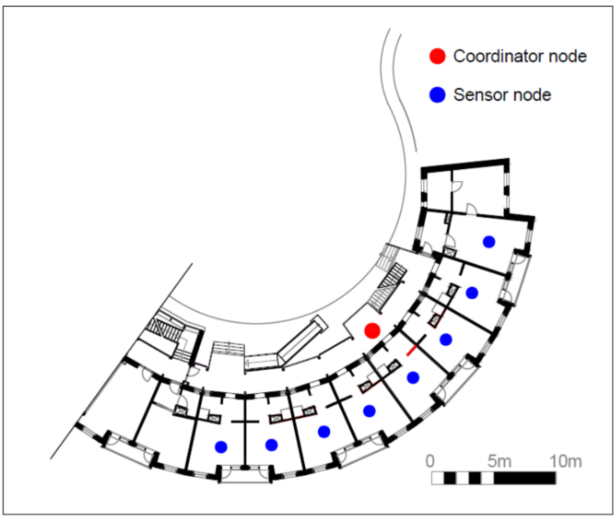


Figure 7.8: Ground floor: suggested setup

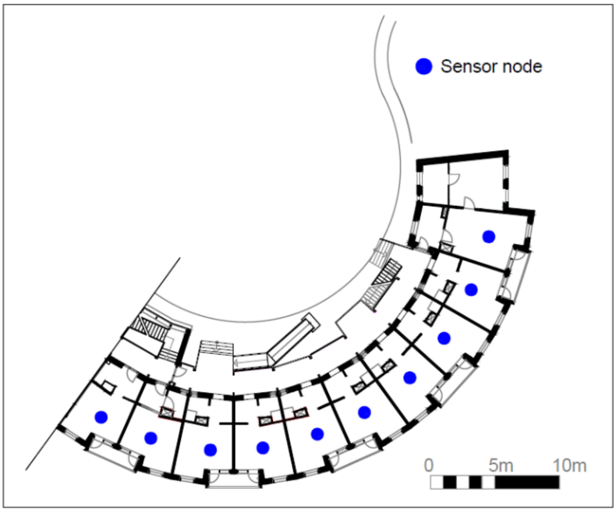


Figure 7.9: First floor: suggested setup

Considering Figure 7.7 through 7.9, it is apparent that the required communication range between any node and the coordinator is less than 20 meters. As such, it is feasible to use the tested ZigBee PRO module, with a 2 dBi antenna, in the setup. Consequently, the suggested setup is an example where it is sufficient to use the star topology to ensure full network connectivity in an operational building. However, this might not be the case, if the ventilation control system was scaled to fit the entire building instead of only half.

7.2.3 Hardware

Given the desired system design, it is possible to select the appropriate hardware. The Libelium Waspmote platform creates the foundation for the setup and was preferred because of its modularity which made it possible to build custom nodes for specific purposes.

As indicated by the plan for the physical setup, the setup consists of three different node types each designed for a specific purpose. In addition to this, the setup requires a signal amplifier and actuators which control the airflow.

7.2.3.1 Synchronization Node

The synchronization node creates the wireless network, can be used as a router for message passing and for saving data from the network in persistent storage. Additionally, the synchronization node enables the possibility of online access and remote control.

Components
1 x Meshlium ZigBee-PRO-AP

Specifications
Processor: 500MHz (x86) RAM memory: 256MB (DDR) Disk memory: 8GB Power: 5W (18V) Power Source: POE (Power Over Ethernet) Normal Current Consumption: 270mA High Current Consumption: 450mA Max Supply Current: 1'5A Dimensions: 210x175x50mm Weight: 1,2Kg Temperature Range: -20°C / 50°C Types of power supply for POE: AC-220V / Battery – solar panel (DC-12V) / Car lighter (DC-12V) System: Linux, Debian. OLSR Mesh communication protocol. Security Authentication: WEP, WPA-PSK, HTTPS and SSH access.

7.2.3.2 Sensor Node

The sensor nodes measures CO_2 levels in each flat and sends the data to the coordinator node. The proposed system contains 18 sensor nodes - one in each flat.

Components (for each flat)
1 x Waspmote ZigBee PRO 1 x Gases Sensor Board v2.0 1 x CO_2 Sensor 1 x SD Card (2 GB) 1 x Rechargeable Battery (6600mA) 1 x USB Cable & Adapter 1 x Generic Casing

7.2.3.3 Control Node

The control node is placed at the ventilation damper and controls the actuator by means of an amplified PWM voltage signal. It receives instructions from the synchronization node in accordance with the logging time specifying new damping levels. The applied conditioning amplifier is a Siemens LOGO programmable relay. Amplification is needed because the control node is unable to perform pulse-width-modulation in the full 10 V range necessary to control the actuator.

Components
1 x Waspmote ZigBee PRO 1 x SD Card (2 GB) 1 x Rechargeable Battery (6600mA) 1 x USB Cable & Adapter 1 x Generic Casing 1 x Siemens LOGO Programmable Relay

7.2.3.4 Actuators

To adjust the dampers in the ventilation system and thus control the airflow, two (one for supply air flow and one for return air flow) Belimo actuators were used.

If individual control of actuators are needed, then a control node is needed for each. Else, the conditioning amplifier can adjust both actuators from one control node.

7.2.4 The Economy

Installation of control and monitoring systems is labor intensive and hence expensive; and even more expensive as retrofits. The Apisseq dormitory is furthermore located in Greenland where the necessary expertise may be unavailable or expensive. A wireless solution was therefore suggested as a way of reducing the installation costs. The economic feasibility and potential advantages is best understood when set in perspective to the price of the standard (wired) solution. Table 7.4 illustrates the expenses of installing a wired control system at the dormitory. However, it should be noticed that the price is based on installation during commissioning of the building. It is therefore reasonable to assume that the cost would be higher now due to the complications of refurbishing the building when it is operational.

Part	Quantity	Sum
Wired CO_2 Sensor	18	74,589 DDK
Cabling	18	11,250 DDK
Prolon input module	1	31,063 DDK
Total		116,902 DDK

Table 7.4: Expenses for the Standard (wired) Solution

As seen in Table 7.5 the retail price of installing the proposed wireless solution is significantly lower.

A notable point is that buying more units would give some discount on the

Part	Quantity	Sum
Sensor Node	18	49,565 DDK
Synchronization Node	1	5,037 DDK
Control Node	1	1,493 DDK
Siemens Conditioning Amplifier	1	448 DDK
Total		56,543 DDK

Table 7.5: Expenses for the Suggested WSN Solution

hardware prices for either solution. However, the listed expenses only covers the upfront costs, leaving operation and maintenance costs unaccounted for.

The standard (wired) solution is fairly robust and low-maintenance where maintenance primarily consists of manually re-calibrating the sensors once every few years. In the case of Apisseq, this and in fact any maintenance tasks are extremely expensive since local service may be unavailable and have to be requested from abroad.

In comparison, the wireless solution makes it possible to handle most maintenance tasks remotely from the existing internet connection, in essence bringing word-wide service to Apisseq without for instance travelling expenses. By doing so, the wireless solution may therefore yield savings in terms of maintenance as well as upfront costs.

Relating to operational costs, installation of a control system is expected to result in an energy rise of about 5%. Under normal circumstances this energy rise would far be exceeded by energy savings generated by improved resource-efficiency. In the case of Apisseq, any control system will be unable to reduce the energy used on ventilation due a poorly chosen ventilation unit. The goal of the solution is therefore to improve the indoor environment that otherwise is subject to over-ventilation. However, the proposed control and monitoring system will generate a good foundation for further research into resource-efficiency with special relevance to wireless solutions. Through tracking of how the wireless solution controls the air flow, it will also be possible to project the operational savings of refurbishing buildings with wireless control systems.

7.3 Scaling the Setup

As seen from Figure 7.8 the coordinator node is placed central in relation to the flats being monitored by sensor nodes, thus ensuring optimal connectivity to all nodes. However, in case the setup is scaled to cover the entire building, it would be prudent to distribute the network as indicated on Figure 7.10.

Figure 7.10: Scaled setup

In the scaled setup the coordinator node is placed at the center of the building to ensure equal connectivity. Though the coordinator node specifications suggest that it is capable of connecting the entire building, signal interferences may prevent communication with nodes far away from the coordinator. It would therefore be reasonable to install a router node, dedicated to message passing, in each wing and thereby secure optimal connectivity to all nodes in the network. In all other respects, the scaled setup is a mirroring of the experimental setup.

7.4 Discussion

During the project the suggested setup was evaluated with special regard to expenses, performance and limitations. The expenses analysis indicated that the upfront costs of the suggested setup would be lower compared to the standard (wired) approach. Additionally, it was indicated that a wireless solution with online access, might reduce maintenance costs in remote regions like Greenland. That being said, using wireless sensor networks as building control systems is a rather new concept where added functionality and services most likely will lead to new challenges. One of the top concerns is the security aspect where wireless systems introduces new risks - especially with online access. It will therefore be important to secure the network and communication properly while also restricting online access. Fortunately, the ZigBee protocol used for communication in the proposed system, facilitates secure communication while additional security layers have added by the Waspmote platform.[Lib13d] Even though a wireless system might introduce new challenges, it must be remembered that it also offers a wide range advantages. Most obviously, it makes it easier and cheaper to install building monitoring and control systems as part of refurbishments. Effectively it could become advantageous to optimize the resource-efficiency of older buildings while thereby enhancing the indoor environment, creating savings from operational costs and benefiting the global climate.

Since the Apisseq dormitory already has a building monitoring system, systems integration would be preferable. It may for instance benefit the ventilation control system to have access to data from the existing monitoring system. Similarly, data extraction and monitoring would be simplified by storing the data from both systems in a shared database. In regard to the suggested setup such integration would be possible through the coordinator node, by granting it access through the dormitory's local network.

7.4.1 Limitations

Though the suggested setup offers many advantages, it has limitations and challenges that need to be considered. Most importantly, the platform is limited to charging 100mA through USB[Lib13c], which is far below what may be possible[USB]. This limitation is problematic since the power consumption often exceeds 100mA and therefore forces the node to use a battery as a buffer. Consequently, careful consideration and configuration of application power consumption is necessary if a node should run indefinitely or without exchanging the battery. Since this limitation is a result of charging the battery through the Waspmote board, it is hypothesized charging the battery separately would circumvent the issue and ensure optimal powering of the node.

In terms of CO_2 sensor quality, a tendency to read measurements which are below the actual gas concentration was discovered. Consequently, multiple evaluations are needed to get reliable and accurate results. An alternate way to increase sensor accuracy might be to extend the sensor warm-up time. It is essentially a compromise between using the power for logging time frequency and sensor accuracy.

As a consequence of influence from thermal and ageing conditions on batteries, the outcome of the energy consideration in Equation 7.2 might be reversed. In such cases, it may be required to extend the sleeping and logging time, to conserve power. To resolve this issue, it was decided to make node applications dynamic, meaning that each node regularly checks the battery status and adjusts the sleeping and logging time accordingly. The drawback of this approach is that the synchronization node no longer can expect measurements to arrive in sync or shortly after each other. Consequently, the control algorithm needs to track arrivals of new measurements and only initiate when enough nodes have reported in.

Chapter 8

Future Work

Considering future work it is necessary to look further into the aspect of energy harvesting and learn how to best prolong node lifetime in the respective phases of the building process. Energy harvesting is especially relevant to the building sector as it also has the potential to improve resource-efficiency even further. Beyond this, it is also necessary consider analysing security and how to prevent exploitation of wireless sensor networks in relation to the building process - especially in regard to remote control and online services.

Due to the increasing traction from the "Internet of Things" (IoT), it will be exciting to follow the developments of Wi-Fi based wireless sensor networks and potentially explore the opportunities.

Relating to the Waspmote platform, it would be necessary to optimize the sensor interface to obtain consistent measurements (e.g. CO_2 sensor). A prerequisite hereof would be to verify if the deviating readings are caused by on-board electronic noise as suspected in this thesis.

Chapter 9

Conclusion

The project succeeded in creating a generic model which eases wireless sensor network design in relation to the phases of the building process. In essence, this thesis describes how to choose network topology, communication protocol, node life-cycle and hardware for wireless sensor network applications in the building industry. It is accomplished through a simple model, which also describes how system requirements may be validated early and thereby avoid faulty design.

Based on the generic model, it became apparent that the daisy chain topology generally is not recommended in the building process. However, it may be useful for temporary setups or setups where limited functionality and minimal installation costs are required. Considering the building process as a whole, it was discovered that the tree topology offered the best overall performance. That said, depending on the application, it may be preferable to prioritize some phases higher than others. It was also shown that the mesh topology has great potential in a mobile context, but that it lacks an open protocol which is supported by third party devices.

In relation to communication protocols it was found that the ZigBee protocol is the most recommended throughout the building process. This was mainly attributed to good support from third party devices and its use of the tree topology, which either is preferred or a reasonable alternative in all the phases of the building process. In comparison, Bluetooth provides some intriguing possibilities from integration with portable devices and vehicles, but is limited by a short communication range and a low scalability.

In contrast, the "Internet of Things" has created traction into development of Wi-Fi-based WSNs. It will be interesting to follow these developments, as Wi-Fi-based WSNs makes it possible to develop applications with high bandwidth and data rate requirements (e.g. video monitoring).

The usefulness of the generic model was proved by applying it to the Apisseq dormitory case story and thereby design a functioning system with the Libelium Waspmote platform. It was here indicated that installation of wireless sensor networks as building monitoring and control systems both created economic savings and added technological advantages compared to the standard (wired) solution. Going further, it was indicated that these gains were even more pronounced in remote regions like Greenland or when installed as part of refurbishments. Effectively it could become advantageous to optimize the resource-efficiency of older buildings, while thereby enhancing the indoor environment, creating savings from operational costs and benefiting the global climate.

By working with the Libelium Waspmote platform some weaknesses were also discovered, which needed to be solved and considered in any future setups.

Most importantly, the Waspmote platform is limited to recharging with 100 mA through USB, which might cause problems since the power consumption often exceeds 100 mA and therefore forces the node to use a battery as a buffer. Consequently, careful consideration and configuration of application power consumption is necessary if a node should run indefinitely or without exchanging the battery.

One of the important design parameters were battery lifetime expectancy, which proved more problematic than anticipated. Though battery lifetime wasn't the focus of the previously published paper [HO14] it was assumed that a lifetime of at least five years would be possible. With the Libelium Waspmote platform is was discovered that long lifetimes are very difficult to achieve without use of alternate power sources like solar cells or other means of energy harvesting. A model for prediction of node lifetime was therefore created to support the generic model. Through experiments it was shown that the predictions were fairly accurate, though thermal and ageing conditions might influence the accuracy greatly.

In terms of sensor quality and conditioning, there were definite problems. It was indicated through the experiments that the humidity sensor either were suffering from poor quality in general or incredibly bad quality control from the manufacturer - as two out of three sensors were defective upon delivery. Beyond this, it was also discovered that the CO_2 sensor has a tendency to read measurements which are below the actual gas concentration. As a work-around for both sensor types it was found that performing multiple measurements and either selecting the highest measured concentration or an average will increase the sensor accuracy. In conclusion it was determined that the the sensors are capable of delivering a good performance, but that some measurements generally are misleading. The deviating readings may possibly be a result of electronic noise from the sensor board and the Waspmote board disturbing the analogue to digital conversion of the signal.

In relation to the node life-cycle, it was discovered that the sensor warm up time actually is the dominating factor in the node execution time. For some sensors, like the tested CO_2 sensor, this was even more pronounced as the warm up time directly influenced the accuracy of the sensor. Consequently, it is for many applications a compromise between using the power for logging frequency and sensor accuracy. For applications requiring a high logging frequency, it was suggested that multiple sensor evaluations might provide acceptable results.

In terms of future work, it is necessary to look further into energy harvesting and learn how to best prolong node lifetime in the respective phases of the building process. This is especially relevant to the building sector as it also has the potential to improve resource-efficiency even further. Beyond this, it it is also necessary to consider analysing security and how to prevent exploitation of wireless sensor networks in relation to the building process - especially in regard to remote control and online services.

WSN has potential to innovate the building industry. The installation is easy and the costs are very low, as seen in this study. The technology is getting better and the hardware is becoming cheaper while it is possible to interface with all kinds of sensors and control devices and machines. This thesis demonstrates these features.

As a result of the work done in this thesis, a conference paper has also been accepted for publication - describing the suggested solution to the Apisseq case story.

Chapter 10

Part II: Papers

This Chapter provides an overview of the collected work, i.e. two papers where I am a co-author and specify how these papers are related to the topic of this thesis.

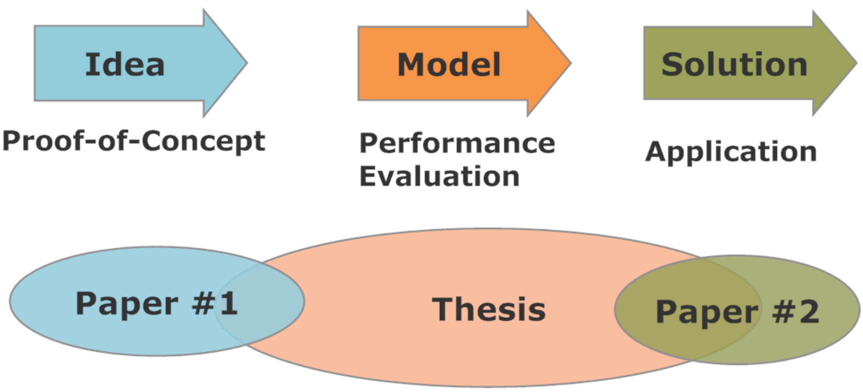


Figure 10.1: Simplified overview of collected work

The first paper described the motivation for introducing WSN technology in the building process - based on a proof-of-concept setup. The paper was written in cooperation with Associate Professor Alfred Heller.

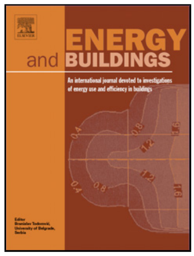
This thesis created a generic model for WSN design in relation to the building industry, evaluated performance and applied this knowledge to a case story in Greenland.

The second paper is a result of the thesis case story and describes the suggested system and its methodology. The second paper was written in cooperation with Associate Professor Alfred Heller and Ph.D. student Martin Kotol.

For simplicity, Figure 10.1 illustrates an overview of the collected work.

10.1 Paper I: Wireless technologies for the Construction Sector–Requirements, Energy and Cost Efficiencies

Accepted Manuscript



Title: Wireless technologies for the Construction Sector–Requirements, Energy and Cost Efficiencies

Author: Alfred Heller Christian Orthmann

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Wireless technologies for the Construction Sector – Requirements, Energy and Cost Efficiencies

Alfred Heller, Christian Orthmann

Department of Civil Engineering, Building 118, Brovej, DTU, Technical University of Denmark, +45 4525 1861, alfh@byg.dtu.dk

Abstract – The construction sector has been rather reluctant with respect to the implementation of ITC innovations that other industries have adopted for years. One of the reasons could be the lack of services by the proposed innovations especially the RFID solutions. This technology is well-researched within the building sector and is therefore used to analyse requirements for alternative technologies. The motivation of the current work is to find upcoming technologies that bring improvements into the sector, for example improved life cycle costs and energy efficiencies, increasing quality, construction and operation efficiency and reducing faults and losses.

The paper also lays out requirements expected by the sector. It will be shown that the wireless sensor network technology is a strong competitor that may meet the requirements. By analysing the application of such technologies throughout the building lifecycle, the utilization can be manifold, hereby minimising overall economic costs and maximising the added values for all involved stakeholders.

Based on the expectations of the sector, the experiences with the introduction of the RFID technology and by estimating the applicability of the extra services that follow the wireless sensor network, the paper will line up the requirements that the new technology has to meet to be introduced successfully.

Keywords: Wireless Sensor Networks; RFID; Building Sector; building lifecycle; requirements, cost, energy efficiency

1 Introduction

The basic idea behind the current work is that there is a need for innovation within the construction and building sector due to, among others, too high margin of errors and necessity of cost reduction. The economic impact of technology can be significant. A Danish consultant report estimated that the savings resulting from error avoidance can reach up to 13-18% of the construction sum [1]. Reduction of losses due to theft, more efficient communication and documentation methods and better construction site management all provide additional economic efficiency.

One of these innovations has been to introduce Radio Frequency Identification (RFID). The technology made no breakthrough within the construction sector as it did in other sectors and industries. The current paper gives some ideas, why this happened. From the experiences with RFID, specifications can be drawn for a new attempt to introduce alternative technologies that are more readily accepted by the construction sector and lead to the desired increase in efficiency, quality, and consequently economical improvements.

The paper proposes wireless sensor networks (WSN) as a promising technology that will bring along a number of additional values. To support the proposal, the value creating services demanded by the sector are analysed and transformed into requirements that the upcoming technology has to meet and that can be tested in further work.

1.1 Motivation

The main motivation of the current work is to reduce the environmental impact of energy usage of buildings. It is our proposal that the application of sensors play a vital role in this respect, enabling insight into the operation and control of the building energy systems. Further arguments for the introduction of wireless sensoring to building processes are:

- Improving efficiency in the building process.
- Improving operational efficiencies including energy performance during operation.

- Economical efficiencies and savings.

With respect to energy efficiencies of buildings, work by the Danish Technological Institute shows potential energy savings between 10-30% by adjusting the different sensors and control settings [2]. Others demonstrate savings based on a commissioning process of between 7-12% [3] and [4], referes to a number of other published work on energy savings due to commissioning. More support are to be found in [5] and [6] which propose energy savings in less quantified terms. The argument of the current paper is that increased flexibility in monitoring systems will entail similar savings as found in literature, but even improve these potentials through e.g. increasing insight, the ability to “debug” the systems and such like. While commissioning is often a onetime activity the above energy savings can be lost due to many reasons, e.g. changes in installations, demands and repurposing of the buildings. Continuous Commissioning is proposed to address these issues and obtain the energy savings for the life span of the building. Flexible sensoring will increase this approach.

Building sensoring is not new. In fact most buildings today are subject to some form of sensoring. Examples of existing building sensoring applications could be: Central or Building Monitoring Systems for large buildings, home surveillance and automation, monitoring and control for small buildings. Today, building sensoring is commonly wired; meaning that the sensors communicate through wiring established in the building. The introduction of wireless sensors brings a number of economic advantages:

1. Expenses for wiring are reduced.
2. Expenses for planning of wiring is eliminated or reduced dramatically.
3. Sensors can be retrofitted even in existing buildings.

Going one step further in the technologies of wireless sensoring, WSN provide even more advantages to the building sector:

1. Flexibility of adding or removing sensors without interruptions or demands for reconfiguration.
2. Inspired by the IT development processes, the application of sensors can bring a new level of monitoring and control into the building, based on known IT skills, tools and procedures.
   a. Testing on basis of standard environments. Running test sequences that can be "knowledge based", e.g. based on AI, simulations and other advanced methods.
   b. Agility/flexibility in hardware and services.
   c. Interface flexibility that is achieved through web-based and other interfaces.
   d. Device flexibility (PC, smart phones and other devices).
   e. Backbone standardizations, flexibility and low cost.

Below, we take a look at the wireless sensor network technology after an historical view on technologies involved.

1.2 From identification towards sensoring – A historical view

The identification of artefacts plays a central role in any process. If you want to control something, you have to be able to identify it. Technologically, this has been addressed firstly by simple labelling that evolved to "tags", and more recently QR-barcodes. To enable identification and at the same time the storage of a minimal set of information, new electronic solutions are developed and we can expect this evolution to continue in the future.

The aim of this section is not to give a comprehensive survey on the history of identification technologies, but rather to show the main aspects of the different steps in the development of identification schemas. Not surprising, some kind of "label" was probably the first kind of identifier of things – You may have seen your grandmothers jam labelled with some stickers with a hand written "identification" – "Strawberry Jam, 1932".

Labels where the only available technology before the IT-revolution and is still widely used. The strength of the technology is its simplicity and low price, whereas the weakness lies in the many things that they cannot provide. Labels must have front-to-front contact with the reader which is a rather pivotal limitation for automatic applications. There are also limitations on the information that can be provided through labels. Some of these shortcomings are resolved in the following technologies.

Radio Frequency Identification (RFID) was already available in 1945 as an espionage device by the Soviet Union for identification. Parallel to this development, transponder-based solutions popped up and a more advanced RFID was presented by Mario Cardullo in 1973. The Cardullo [2] technology was introducing as a transponder with memory, hence being able to relate the identification with extra meta-data/information read by external readers. Michael [3] presents a history of automatic identification technologies, from bar codes, to magnetic-stripe cards, smart cards, biometrics and RFID tags, with a very large literature survey on the topic. A reasonable set of applications throughout history are stated by Russos and Vassilis [4].

RFIDs are small electronic devices that can be incorporated in almost any kind of object, clothes, devices, food wrapping, and can be applied almost everywhere. The information is accessed through a reader with no contact, overcoming the limitation of the label’s need for front-to-front contact between the “tag” and the reader, and enables automation of this process, reducing labour requirements. The technology is designed in three basic types, “passive” not using any batteries and activated by the readers, “active” that use batteries to actively communicate with readers, and a third that combines the two by activation of passive devices to an active mode. In any case, the strength of the technology is its simplicity and low price, whereas the drawback of the technology lays in the limited memory capacity. However, at an early stage the strength of the Internet was coupled to overcome this limitation – connecting the identifier to an internet address provides new opportunities for information storage and new business models of pooling of information, as we will see below.

In addition to RFID, there are various kinds of wireless technologies including mobile phone solutions and communication solutions such as WIFI, both are capable of communicating over large distances. On the other end of the spectrum there are "near field communication" solutions.

To establish evidence for the relevancy of the introduction of the alternative technology, the well-known and well-researched RFID-technology is analysed for their proposed impacts and lack of capability reported in literature. Using RFID-technology as a basis, more advanced wireless sensor network technology is examined for further testing of the hypothesis. Identification is one of the main features of both mentioned technologies, but both lack globally uniqueness.

In the current paper an alternative approach "Wireless Sensor Networks" will be proposed, solving the limitations of the RFID solution and providing additional benefits. Before doing so, the application of RFID within building construction and building management is examined to give an idea of the potentials for such technologies and also give us specifications for the functionalities that ought to be met by an alternative solution.

2 RFID in construction and building sector

To establish evidence for the relevancy of the introduction of the alternative technology, the well-known and well-researched RFID-technology is analysed for their proposed impacts and lack of capability reported in literature. Using RFID-technology as a basis, more advanced wireless sensor network technology is examined for further testing of the hypothesis.

In 2006 the application of RFID within the building sector or building management was rather limited even though billions of devices where used in the food industry, warehousing, industrial production, and especially supply chain management involving different actors [4]. A report by ERAbuild [5] gives a comprehensive overview of the subject and reports on applications and research work. The conclusion was that the achievements from other sectors and industries ought to be exploited in the building sector, such as:

1. *direct and automated surveillance maintenance programmes by a click on a PC or PDA*[1]
2. *inventory control*
3. *control of right equipment at right place*
4. *reduction of data entry errors both during 'production' and afterwards in maintenance*

However, the report concludes that the implementation in the building industry had not been seen in 2006, even though vendors from industries did act as drivers for the development. A rather important finding was reported by The Danish Building Research Institute [6]:

In the construction value chain from manufacturer of building materials, distributors, constructors, operators and end users many advantages can be achieved from embedded technology (RFID). However there are very different demands and needs to performance of technology in the different groups.

The main application for RFID is reported to be related to facility and asset management, but also access control to building sites. These applications tend to give pay backs in form of immediate savings. Cases are reported where construction details, drawings and instruction videos on the web are linked through a RFID and related "tag" information. The application of Building Information Models (BIM) in relation to RFID tags are reported, enabling real time tracking of construction progress, similar to a supply chain monitoring.

As we will find below, the current research takes this diversity into consideration. The report by [5] finally concludes:

At this stage in use and development of RFID in Construction we must realise that there are many questions and few answers, most cases that we have been investigating are pilots and not full-scale implementations,

[1] Note that the device technologies have changed in time.

many research papers and development projects have caused great interest and many observers but not any steps into fulfilment of RFID strategies.

Since, the application of RFID is still on-going: Chang, Hung and Peng [7] proposes the application of RFID in combination with sensors cast into wall constructions, and many other applications for crack monitoring are reported. Jacobsen and Poulsen [8] propose the introduction of RFID for quality control and [9] proposes the application of RFID for material identification. Such efforts are sporadic and no master plan seems to lead the development. In the meantime other technologies are pushing, amongst them the Home Entertainment and Surveillances segment, applying wireless Zigbee, Z-wave and other wireless communication technologies. Building health monitoring applications are also presented in research, [10] and [11], applying the below promoted sensor network technology.

By analysing the literature of the involved technologies a number of findings can be extracted. Chang et all. [12] Table 3 and 4, show clearly that the RFID technology was published widely but with low “depth of investigation” in many sectors and industries, the construction industry accounts for 4 out of 316 published papers. These findings are also supported by [1].

2.1 Economic considerations based on construction lifecycle costs

The building lifecycle is e.g. defined in [13] to consist of the following phases: pre-design > design > construction > operation > refurbishment > decommissioning > deconstruction and demolition. By simplifying to relevant tasks for the current study and adding commissioning to the lifecycle, due to the fact that quality assurance and energy efficiency is documented and established at this stage, we use the following lifecycle in the current work:

construction > commissioning > operation > refurbishment > decommissioning > demolition

Regarding commissioning: There are numerous reports on flaws and errors that could be handled during this phase that would lead to a long-term increase in efficiencies. The current system proposal supports commissioning especially well due to its flexibility, where sensors can be added or removed dynamically without disturbing the operation of the network and with no configuration necessary. This is one of the most powerful features of this technology.

The hypothesis of this work is that - *The introduction of state-of-the-art identification, sensor and communication technologies to the building lifecycle leads to significant economical, technical and societal gains. If sensors are wireless, especially in form of wireless sensor networks, these gains are even more pronounced.*

One of the main arguments for the current solution is that by repurposing the id and sensor components during the lifecycle of buildings, the economic costs become insignificant and the values due to increased services result in efficiency improvements on many performance parameters of the building. The current paper investigates the application of wireless sensor technologies in the given lifecycle-phases and documents the potential of repurposing of the same sensors for different conditions throughout the lifecycle.

3 Wireless Sensor Networks for the Construction Industries

It is apparent from the above status on the application of RFID that there are significant technological and logistical improvements that have not been utilized within the building sector. Hence a more advanced technology is required. In the current paper a wireless network technology is proposed that adds additional services to the identification devices. Due to the fact that the technology is combining many sub-technologies, see Figure 1, it will be presented in detail here.

WSN provides identification of the sensors by wireless communication and storage of information in its memory. This is very similar to RFID. The advance comes from the combination with sensors that add information from the surroundings, and network communication capabilities. The implication of these will be explained below. In the following a brief introduction to the terminology used in this report is presented.

A WSN consists of a variety of configurations of distributed “nodes”. The individual nodes can be of different types:

Synchronization node: A node which collects data from other nodes in the network and possibly sends the synchronized data to a PC or server. Synchronization nodes are in some cases called Terminals or Gateways.

Node / Sensor node: A device collecting data through sensors and possibly sends collected data to synchronization nodes. Sensors typically monitor environmental or physical conditions like humidity and temperature.

Nodes are capable of communicating in “hops”; meaning that they communicate with devices in the network through each other. This means that any two nodes in a wireless sensor network can communicate by having messages or data passed through other nodes. Effectively, nodes don’t physically need to be within the communication range of their targets to communicate.

3.1 Functionalities required derived from the building lifecycle application

From the above investigation on RFID and the analysis of the demands of the building cycle, we propose the following utilization of the wireless technology for the building lifecycle:

- Production (quality assurance, documentation, facility management)
- Transport (event registration)
- Construction (identification, facility management, assembly support)
- Commissioning (documentation, adjustments)
- Operation (monitoring, optimization)

- Disposal (identification, metadata, waste management)

Services that a future technology must provide that correspond with the proposed utilization:

- Documentation of building components (identification, information storage)
- Easy communication of id and information with existing technologies
- Remote access
- Online warnings - testing
- Flexibility (add and remove sensors in running system with no reconfiguration)

The added values of such a solution are:

- Reduction of errors during design, construction, commissioning, operation.
- Better building performance due to better monitoring (energy, indoor environment).
- Better facility management services due to increased information.
- Cheap and standardized technologies (outside the network itself).

From the collected functionalities the following requirements can be derived for the communication technologies that are to be investigated":

Basic functionalities: These are "identification" of the sensor, memory for minimal information storage over time, which are very similar to the RFID technology. Due to the fact that WSN do store sensor data, the memory space is much larger than for RFID solving this limitation.

Wireless communication: RFID stays passive in regard to communication, while WSN broadcast according to the requirements of the given application. The interval of broadcasts, the amount of information communicated and the strength of the antenna, all contribute to the characteristics of the actual applications. It also has a large impact on the battery lifetime, discussed separately.

RFID can only communicate to special devices (base stations), while the nodes of WSN can communicate with each other, called "communicating in hops". This introduces much wider application of this technology.

Due to the fact that synchronisation nodes do not have to be very advanced, it is possible to use many in the same installation adding another set of flexibility into the overall solution, e.g. changing from special protocols and tools to well-established IP protocol that enables the utilization of the many tools that are compatible with the internet protocol. This again gives a large space of freedom in system design and economical savings, because no special hardware is used for handling the collected data and information.

Positioning – localisation: This functionality is not really a demand by the sector, but is an extra service by WSN that provides many possibilities for localisation of material, components, people and others.

Long lifetime of battery: The weakness of WSN is the battery lifetime. There are a few strategies to overcoming this obstacle:

1. Saving energy demand is the most applied solution. This is achieved by optimizing all energy related parameters of the nodes, leading to the wide range of different WSN solutions instead of standardisation. An important requirement here is the demand for state changes where the node changes its behaviour, e.g. frequency of sensor readings and broadcasts, to limit energy demands.
2. Increasing the battery volume which is expensive and requires more space.
3. Introducing energy harvesting in any means. This is an on-going research and development area.
4. Wiring for energy supply, destroying the wireless concept. On the other hand, the wiring can be cheap, simple and short distance.

5. Wireless energy supply, which also is under development and cannot be implemented as a commodity solution.

3.2 Discussion and further work

The paper analyses the lack of break-through for the RFID technology within the construction sector, despite the demand for innovation to reduce the number of errors and improve overall construction efficiency. By analysing experiences from the technology a number of demands were found, which could be transformed into requirements for an alternative technology that may have the chance for widespread implementation in the sector and hereby lead to the expected gains. In future work the requirements can be tested on WSN and other technologies.

A common concern in a WSN is the necessity of batteries in general and especially the battery lifetime. The issue is discussed in literature and several sources mention battery life times in WSN of up to 30 years; even when sending data every minute. [14] [15]. Most sources like [16] only guarantee battery life of about 5 years.

Another untouched question is what limits there are on the range of nodes in a WSN. This is dominated by the antenna characteristics and should be studied very carefully. There exist both long- and short-range WSNs, thus making it possible to fit the network to the application needs. In [17] a long range WSN was tested with a node range of 13.2 km, however the nodes were of significantly larger size than the Sun SPOTs used in the project-experiments. Examples of nodes with a more realistic size for the intended applications are described in [18] these nodes had a range of about 300 m. In regard to the building process 300 m is more than enough for most cases and it could be argued that a smaller range would do as well due to WSNs' ability to communicate in hops. Node range has a dramatic impact on battery lifetime.

The interaction of building information models (BIM) with identification technologies such as RFID and WSN will also be relevant to investigate.

The current study indicates that it is technically feasible to utilize wireless sensors in a network throughout the building process. That said, several important issues were identified and solutions should be considered carefully in preparation for further development.

Introducing sensors with identification capacities at similar costs enhances the services during the lifecycle of building design and construction, enabling the sensors to adjust to the relevant mode of operation. This way the cost of these extra sensors will be funded in the earliest stage of the lifecycle, while still generating savings during the remaining lifecycle stages.

One open question is the possibility for integration of the wireless sensor network with Building Monitoring Systems (BMS) and CMS. The proposed internet connected WSN has its own “backbone” infrastructure (server, database and similar). Hence questions arise on how to integrate them, if the backbone is redundant, or opposite the backbone is an important support and gateway for the BMS. Questions also arise on how to integrate with other wireless services such as Home Automation and more. This is left to later research.

The ability of localisation of the WSN technology increases the service pallet even further, enabling reasonably exact localisation of the sensors themselves and hereby moving objects and even humans, thus enabling emergency situation management and much more.

This vision has already been demonstrated in various implementations. A Danish consultant company, BMT Instruments, provides a moisture monitoring service for clients that have access through the internet to their data. Many others examples can be found. The limitation of these implementations is that they are proprietary, which blocks changes to the behaviour of the sensors, the network and its communication. Therefore research with such systems is very limited in their purpose of designing next generation wireless solutions for the construction sector. Therefore future work will be to develop an open platform implementation that overcomes these barriers. The idea is to design the hardware on open components and build the software infrastructure based on open protocols. The only exception to that is the communication between sensors and the terminals that may depend on some proprietary protocol, whereas the rest is handled within the web technologies.

Another future development that would implement actuation and decision automation into the overall technology, is described for “Smart Objects”, [19], where both RFID and WSN would play a role. Here, more intelligence is placed into the sensors; even going so far as to utilize “embedded systems” into the individual sensor units.

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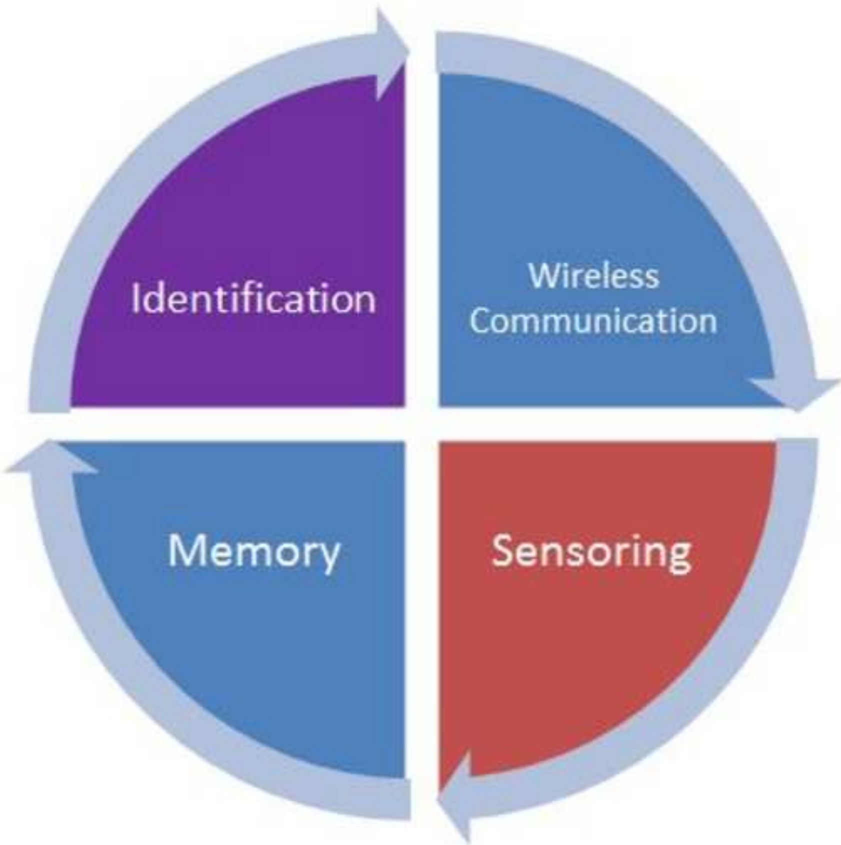
Table of Figures:

Figure 1


Identification
Wireless
Communication
Memory
Sensoring

10.2 Paper II: Introduction of flexible monitoring equipment into the Greenlandic building sector

Introduction of flexible monitoring equipment into the Greenlandic building sector

Martin Kotol[1], Alfred Heller[1*] & Christian Orthmann[2]

[1] Section of Building Physics and Services, Department of Civil Engineering, Technical University of Denmark. DK-2800 Lyngby, Denmark

[2] Department of Applied Mathematics and Computer Science, Technical University of Denmark. DK-2800 Lyngby, Denmark

[*] Speaker, e-mail: alfh@byg.dtu.dk

Abstract

Greenlandic winters are long and cold so living inside the heated and properly ventilated space requires quite some energy. It is assumed that in mechanically ventilated buildings, significant amounts of energy for heating can be conserved by adjusting the ventilation flow rates according to actual demand of the occupants. Traditional solutions available on market consist of controller and sensors in the living space detecting the occupancy and activity (movement sensors, CO_2 sensors, Humidity sensors, etc.). The controller needs to be programmed and maintained by an expert and sensors need to be hardwired to the controller. In Greenland where price of the labor is very high and availability of experts limited the installation of such control system becomes unacceptably expensive, particularly in case of renovation of existing buildings. One possible solution to the above is to introduce wireless sensor network (WSN) technologies. The design of a prototype wireless monitoring and control system is demonstrated in the new dormitory Apisseq in Sisimiut, Greenland. The existing mechanical ventilation was running at a constant air volume even during unoccupied hours which resulted in a very high heat demand. It was estimated that installing the WSN system will bring annual savings of 1,600 € at the investment of 8,000 €. This paper describes the initial setup of the system and discusses its advantages and drawbacks.

1. Introduction

The Arctic climate is cold, so living inside heated buildings requires great amounts of energy. In Greenland households account for 25 % (85 % is heat and 15 % is electricity) of the total energy consumption (Statistics Greenland 2011). The average heat consumption of households in Greenland was 387 kWh/m^2 in 2009 (Statistics Greenland 2011). Additionally, another 25 % of the Greenlandic energy is used to deliver energy and water to the consumer (including households) hence the real contribution of households to the overall energy use is higher than 25 %. With the intention to reduce the CO_2 emissions, the overall energy use needs to be reduced accordingly. Given the amount of energy used in buildings, these cannot be excluded from the process of energy conservation. To reduce the energy use, buildings will become more insulated and air tight to minimize heat losses. Furthermore, the buildings need to be equipped with advanced heating, ventilation and air conditioning (HVAC) systems to ensure healthy and comfortable indoor environment. It has been shown that by optimizing the operation HVAC systems according to occupants' actual demands can bring further substantial energy savings (Nielsen and Drivsholm 2010; Laverge et al. 2011). However installing conventional wired control systems may become costly particularly in case of retrofits as the expenses related to installation of the systems are high. A special case is buildings in remote regions like Greenland where availability of professional labor is limited and expensive.

A possible way to reduce the installation costs is the use of Wireless Sensor Networks (WSN) to monitor and control buildings. The purpose of this study is to develop WSN based monitoring and control system and implement it into an existing building with HVAC system. This should bring energy savings without negative effects on indoor air quality (IAQ). Furthermore it should be demonstrated that the investment is lower than the conventional wired solution and the return on investment is reasonable.

2. The building description

The studied building is a dormitory for engineering students Apisseq in the town of Sisimiut, Greenland. It was built in 2010 with the intention to demonstrate energy efficient building in which the modern technologies, not yet commonly used in the Arctic, could be installed and tested. Previous studies undertaken in this building have shown, that the poor design of the ventilation system causes that the building is constantly over-ventilated (Kotol and Rode 2012) which in such cold climate means significant increase of the energy use.

2.1 Layout

The building has a circular shape and consists of three floors: a ground floor with technical rooms and two upper floors with flats, laundry and common room. There are 33 single room flats for one student and 4 double room flats at the gables of the building (see Figure 1).

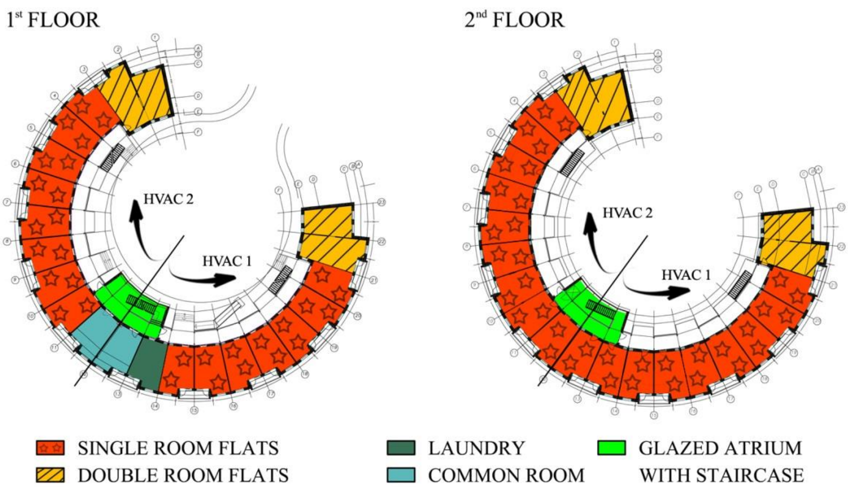


Figure 1. Floor plans of the engineering dormitory Apisseq

More detailed description of the building can be found in (Kotol and Rode 2012; Vladyková et al. 2010). The annual heat demand was estimated to 160 MWh/yr for space heating and 80 MWh/yr for domestic hot water (DHW). In total the predicted annual heat demand was 240 MWh/yr or 169.7 kWh/(m^2·yr). However, the real annual heat demand in 2012 was 310 MWh/yr or 219.7 kWh/(m^2·yr). Out of which, 18 % was dedicated to heating of the ventilation air. This in terms of running costs resulted in total annual energy bill of 30,000

€ in 2012 (of which 5,400 € was related to ventilation air heating).

2.2 Ventilation system

The ventilation system consists of two identical HVAC units. Each of them is venting half of the building as shown in Figure 1. The units deliver fresh air to the living space of each flat and extract the polluted air through range hoods and bath rooms of each flat. The supply air is delivered at a constant rate whereas the exhaust air flow can be increased in case of increased humidity in bathrooms or cooking activities but at the normal operation the ventilation is balanced and provides the air change of 1.1 h^{-1}. Nevertheless, the current Greenlandic building regulation (GBR) (Direktoratet for Boliger og Infrastruktur 2006) requires the minimal air change of 0.5 h^{-1}. The GBR also requires that the following rooms should be equipped with air extraction: Kitchens (20 l/s) and bathrooms (15 l/s). This additional requirement was likely the reason for designing the constant ventilation rate of 20 l/s (air change of 1.1 h^{-1}). However, the required extraction from kitchens and bathrooms is meant to be available when needed and does not have to be on at all times. It is expected that substantial energy savings can be achieved by reducing the ventilation air change according to the actual demands (occupancy) without negatively affecting the indoor air quality.

3. Methodology

To detect the actual occupancy and estimate the right amount of ventilation air needed for the space, CO_2 concentration is often used. Some European standards suggest that in case of demand controlled ventilation where indoor CO_2 concentration is used as an IAQ indicator the ventilation rate can be adjusted in order to maintain the indoor CO_2 concentration below certain level [1000 ppm (Danmark. Erhvervs- og Byggestyrelsen 2010) or 500 ppm above outdoors (Dansk Standard 2007)]. The minimal air change of 0.05 $l/s{\cdot}m^{-2}$ to 0.1 $l/s{\cdot}m^{-2}$ (Dansk Standard 2007) should however always be maintained.

3.1 Experimental setup

In this experiment the ventilation system in one half of the building will be adjusted to reduce ventilation rates according to actual demands of the occupants. The other half of the building will remain unchanged to provide a reference case for evaluation of the improvements.

Due to the design of the ventilation system and the fact that the building is already finished and in use, the space for improvement is rather limited. For that and for economic reasons it would not be economically feasible to control the air flow on a room level. Nevertheless, as the building is a dormitory for students with similar schedule, it can be expected that their daily routines will have a similar pattern for majority of the time. Therefore the air flow will be regulated centrally on the ventilation unit level.

Although the air flow will be adjusted centrally for the entire half of the building, it is still important to make sure that none of the flats will be insufficiently ventilated. Therefore a CO_2 sensor will be placed in each flat. To avoid excessive installation costs related to hard wiring each sensor, the sensors will communicate wirelessly with the central node. The central node will evaluate levels of CO_2 in the rooms and send a control signal to the actuators which will adjust the air flows. The actual air change will be controlled in the range between 0.02 h^{-1} and 1.1 h^{-1} in order to maintain the CO_2 concentration in each room below 1000 ppm.

Furthermore the central node will be accessible on-line which will further reduce the costs as all the programming, calibration, software maintenance, troubleshooting and data collection and evaluation can be done remotely from anywhere in the world.

4. Hardware

The Libelium Waspmote platform creates the foundation of the setup and was preferred because of its modularity, which made it

possible to build custom nodes for specific purposes.
The experimental setup consists of three different node types (each designed for a specific purpose), a signal amplifier and damper actuators which control the airflow.

4.1 Central Node

The central node creates the wireless network, it can be used as a router for message passing and it saves data from the network in persistent storage. Additionally, the node enables the online access and remote control. The coordinator node selected for this experimental setup is the Meshlium ZigBee-PRO-AP.

4.2 Sensor Nodes

The sensor nodes monitor CO_2 concentration in each flat and send the data to coordinator node. The proposed system contains 18 sensor nodes (one in each flat). The main components of the nodes are Waspmote ZigBee PRO, Gases Sensor Board v2.0 and solid electrolyte CO_2 Sensor TGS 4161. Each node has a 6.6 Ah battery which will be able to power the node for a year. However, for the experimental purposes each node will be powered from the electrical grid as a backup.

4.3 Control Node

The control node (Waspmote ZigBee PRO) receives the commands from central node and by means of two actuators (Belimo TF24-SR) adjusts the supply and exhaust damper positions (and thus air flows). Because the voltage range given by control node is 0 V to 3 V and the actuators require a signal from 0 V to 10 V an amplifier was needed. For this purpose a programmable relay Siemens LOGO which is already a part of the building's inventory was used.

5. Economy

Excluding the Belimo actuators and Siemens LOGO relay (which are already installed in the building), the retail price of the wireless solution was 8,000 €. For comparison the price of the wired solution would be 16,000 € (according to Table 1).

Table 1. Price estimation for the wired solution

Item	Price (incl.VAT)
CO_2 sensors (Vaisala CARBOCAP® GMW 22)	6,000 €,
Programmable logic controller with web server (Prolon PID 4000) including installation	4,000 €
Installation of the sensors	6,000 €
Total	**16,000 €**

Expected annual energy savings brought by this solution are 15 MWh/yr or 1600 €/yr at current price of the heat. This yields simple payback time of 5 years compare to 10 years with standard wired solution.

6. Discussion

The price of the wired solution is higher partially due to use of different CO_2 sensors. The Vaisala sensors use more accurate technology and do not require such frequent calibration (the manufacturer guaranties 5 % accuracy over the course of five years). On the other hand the wireless solution allows remote calibration on as frequent basis as required by the sensor manufacturer, therefore more accurate sensors are not needed.

The price for installation of the wireless sensors has not been included in the calculation as that will be performed by the researchers. However, installing the wireless solution only requires attaching the sensor nodes to a wall in each flat and connecting the central node to the internet (the rest is done remotely). This is apparently less labor intensive than wiring each sensor through the finished building in use. Moreover it does not require highly skilled professionals to perform this work.

The actual payback period will strongly depend on the real energy savings and will also be affected by the energy price. The price is expected to be rising every year which will further shorten the payback period.

One of the advantages of WSN solution is its flexibility/expandability. If in the future the system needs to be expanded by large number of sensors (e.g. including the other half of the building), these can simply be added to rooms without the need for additional central node. Contrary the wired solution has a limitation in maximum number of inputs from sensors, once this number is reached, additional hardware must be installed.

A possible drawback of the WSN solution can be its robustness and long term reliability. These will be tested during the experiment.

7. Conclusions

It was found that it is economically beneficial to use WSN instead of traditional wired solutions in remote areas with expensive labor and limited availability of highly skilled workers.

The simple payback period is 5 years which will probably be even shorter due to increasing price of energy.

The real energy savings and actual payback period along with the reliability of the solution will be confirmed by the experiment.

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Appendix A

Waspmote: Tasks

This appendix lists rough time estimates for typical tasks performed with the Libelium Waspmote Platform.

Task	Category	Time	Comment
Turn ZigBee Module ON	Communication (ZigBee)	3.5 s	Gives it time to start
Turn ZigBee Module OFF	Communication (ZigBee)	0.01 s	
Set Network Parameters	Communication (ZigBee)	10 s	Because it is necessary to wait for the wireless module to set the parameters
Join Network	Communication (ZigBee)	0.6 s - 2 s	Including check of network parameters
Compose Message (frame)	Communication (ZigBee)	0.01 s	Does not require module to be turned ON.
Receive and Parse Message (frame)	Communication (ZigBee)	0.2 s	This may wary depending on connection.
Send Message (frame)	Communication (ZigBee)	0.1 s	This may wary depending on connection.
Pulse-width modulation (PWM)	Power	0.1s	
Configure Sensor	Sensor Board	0.1 s	
Warmup CO_2 Sensor	Sensor Board	30 s - 10 min	Depending on accuracy requirement
Warmup Humidity Sensor	Sensor Board	15 s	
Warmup Temperature Sensor	Sensor Board	0.1 s	
Warmup Atmospheric Pressure Sensor	Sensor Board	0.02	
Warm up CO Sensor	Sensor Board	1 s	
Warm up O_2 Sensor	Sensor Board	15 s	
Warm up NO_2 Sensor	Sensor Board	30 s	
Warm up NH_3 Sensor	Sensor Board	0.25 s	
Warm up CH_4 Sensor	Sensor Board	30 s	
Warm up Liquefied Petroleum Gas Sensor	Sensor Board	30 s	
Warm up Air Contaminants Sensor	Sensor Board	30 s	
Warm up Solvent Vapors Sensor	Sensor Board	30 s	
Warm up O_3 Sensor	Sensor Board	30 s	
Warm up VOC's Sensor	Sensor Board	30 s	
Measure Sensor Level (any)	Sensor Board	0.1s	
Create file (SD card)	Storage	0.1s	
Delete file (SD card)	Storage	0.1s	Depends on size
Append to file (SD card)	Storage	0.1s	Depends on size
Read from file (SD card)	Storage	0.1s	Depends on size

Table A.1: Time estimates for typical tasks

Appendix B

Waspmote: Power Consumption

This appendix lists the official power consumption estimates with the Libelium Waspmote Platform (originates from [Lib13e] and [Lib13a]).

20. Energy Consumption

20.1. Consumption tables

Waspmote

ON	15mA
Sleep	55µA
Deep Sleep	55µA
Hibernate	0,06µA

XBee

	ON	SLEEP	OFF (Waspmote switches)	SENDING	RECEIVING
XBee 802.15.4	50,36mA	0,1mA	0µA	49,56mA	50,26mA
XBee 802.15.4 PRO	56,68mA	0,12mA	0µA	187,58mA	57,08mA
XBee ZigBee	37,38mA	0,23mA	0µA	37,98mA	37,68mA
XBee ZigBee PRO	45,56mA	0,71mA	0µA	105mA	50,46mA
XBee 868	60,82mA	--	0µA	160mA	73mA
XBee 900	64,93mA	0,93mA	0µA	77mA	66mA

Bluetooth Module

ON	14 mA
OFF	0 mA
Scanning	40 mA
Sending	39 mA
Receiving	20 mA

GPS

ON (tracking)	32 mA
OFF (Waspmote switch)	0µA

GSM/GPRS

Connecting	~100mA
Calling	~100mA
Receiving Calls	~100mA
Transmitting GPRS	~100mA
SLEEP	1mA
OFF	~0µA

3G/GPRS

Connecting	~100mA
Transmitting/Receiving GPRS	~100mA (1,2A – 2A during transmission slot every 4.7ms)
Transmitting/Receiving 3G	~300mA - 500mA
SLEEP	1mA
OFF	~0µA

SD

ON	0.14mA
Reading	0.2mA
Writing	0.2mA
OFF	0µA

Accelerometer

Sleep	0,08mA
Hibernate	0,65mA
OFF	~0µA

6. Consumption

6.1. Power control

On one side, the control of the Gases 2.0 board power can be carried out using the Waspmote's general on/off system for the 3.3V and 5V supply lines, which allows the board to be totally switched on and off (0uA).

On the other hand, specific control mechanisms have been installed inside the sensor board using a system of solid state switches, allowing the independent digital control of each sensor power without the need to physically access the circuit, except for the humidity and temperature sensors, which are powered always the board is on. This way, activation and reading of each sensor can be programmed at the same main code, controlled by the microcontroller. In section "API" where the API libraries related to this board are presented and the use of each of these switches is clearly and precisely described, as well as the correct way to read each sensor.

6.2. Consumption table

In the following table the consumption shown by the board when active is detailed, from minimum consumption (constant, fixed by the permanently active components, such as the adaptation electronics and temperature and humidity sensors).

To find out the total consumption of the board with sensors integrated to the consumption of each connector, the consumption of each chosen sensor must be added together. This consumption can be consulted in the section for the sensor itself when all its characteristics are described.

	Switch ON	Switch OFF
Minimum (Constant)	2mA	0mA (Waspmote switch)
Connector 1-A (without sensor)	0mA	0mA
Connector 1-B (without sensor)	0mA	0mA
Connector 2-A (without sensor)	0mA	0mA
Connector 2-B (without sensor)	0mA	0mA
Connector 3-A (without sensor)	0mA	0mA
Connector 3-B (without sensor)	0mA	0mA
Connector 4 (without sensor)	0mA	0mA

6.3. Low Consumption Mode

From the point of view of optimizing Waspmote resources when the Gases 2.0 board is used, it is recommended that the following instructions are followed:

- **Keep the board switched off while no measurement is being taken**
  This is the most efficient method of lowering consumption when none of the parameters are being continually monitored. To completely disconnect the board's power, disable the switches that allow passage of the 3.3V supply, the 5V supply from Waspmote (using the `SensorGasv20.setBoardMode` library function) and to the two I2C bus channels (SCL and SDA) using the command shown in the WaspmotePWR library (more information on this can be found in the API manual). Do not forget to reconfigure gain and load resistances when switching it on again.

- **Optimize the time the sensors are switched on depending on your application**
  The accuracy of each sensor's measurement which can be obtained will vary depending on the time that it remains switched on or on the power supply cycles which are continually applied, depending on the type of sensor. Knowing the time required to take a measurement in a determined application will allow saving of consumption without losing resolution in the sampled value.

- **Simultaneously activate the minimum number of sensors possible**
  Given that the current allowed in the digital switches' output is limited (about 200mA), it is recommended to not overload them by activating a number of sensors at the same time which in total may surpass this current.

Sensor	**Consumption**	**Comment**
Humidity	0.5mA	0.38mA typical consumption
Temperature	12μA	6μA typical consumption
Atmospheric Pressure	10mA	7mA typical consumption
CO	3mA	only average consumption listed
CO_2	50mA	only average consumption listed
O_2	0μA	
NO_2	26mA	only average consumption listed
NH_3	12mA	only average consumption listed
CH_4	61mA	only average consumption listed
Liquefied Petroleum Gas	61mA	only average consumption listed
Air Contaminants (TGS2600)	46mA	only average consumption listed
Air Contaminants (TGS2602)	61mA	only average consumption listed
Solvent Vapors	56mA	only average consumption listed
O_3	34mA	only average consumption listed
VOC's	32mA	only average consumption listed

Table B.1: Gases sensor power consumption

Appendix C

Communication: Backwards Compatibility

This appendix originates from [Bac] and illustrates, in Figure C.1, the backwards compatibility of popular communication protocols.

	Availability	Backwards Compatibility
Bluetooth	11 years	Compatible with all previous versions at base 1Mbps
Bluetooth low energy	New	Will be compatible with Dual mode chips introduced in 2011
802.11	13 years	Security is compromised in mixed versions more than 3 years old
Wi-Fi	10 years	Security is compromised in mixed versions more than 3 years old. Two incompatible frequencies of operation – 2.4GHz and 5.1GHz
ZigBee	6 years	Three version – all with compatibility issues
ZigBee PRO	3 years	Incompatible with ZigBee
ZigBee PRO SEP2.0	New	Incompatible with other ZigBee stacks
ZigBee RF4CE	2 years	Incompatible with other ZigBee stacks
ANT	3 years	Only one version available.

	Average years of compatibility
Bluetooth	11 years and still compatible
Wi-Fi	3 - 5 years (at which point security is compromised)
ZigBee	2 years

Figure C.1: Backwards compatibility of popular communication protocols (2010); originates from [Bac]

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