System design choices in smart autonomous networked irrigation systems

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Sammanfattning

Trådlösa sensor nätverk används för att övervaka lokala miljöförändringar med hjälp av olika sorters sensorer. På grund av nedåtgående driftkostnader (ökad tillgänglighet av open-source mjukvara) och framsteg inom processor-, radio-, och datorminnesteknolgi har både tillgängligheten och användningsområdena för trådlösa sensornätverk stadigt ökat.

Sigma Technology Development AB ställde frågan huruvida ett trådlöst sensornätverk, som använder sig av ett open-source operativsystem och kommunicerar över IPv6, kunde användas inom smart konstbevattning? Företaget ville även att ett proof-of-concept system utvecklades för demonstration samt för att kunna avgöra om de designval som gjorts är lämpliga att använda i en verklig implementation.

Det finns en mängd designval som måste göras när man konstruerar ett bevattningsystem: back-end lösningen, vilka bevattningsalogritmer som ska användas, vilken hårdvara som ska användas samt hur kommunikationen mellan noderna ska upprättas? Det här examensarbetet fokuserar därför på den övergripande systemdesigen av ett trådlöst sensornätverk inom konstbevattning, utvärderar och avgör vilka kompromisser som måste göras samt för- och nackdelarna med dessa val.

Examensarbetet presenterar vidare två förbättringar på det utvecklade konceptsystemet som inte heller finns på marknanden. Först rekommenderas användandet av robusta självläkande routing protokoll trots påstådda energiförbrukningsproblem. Sedan föreslås även en teknik som minimerar energiåtgången genom att dynamiskt ändra hur länge sensornoden befinner sig i ’sleep mode’, detta med hjälp av insamlad väderdata. Slutligen så konstrueras och analyseras proof-of-concept systemet för att utvärdera om dessa designval är lämpliga för en implementering i det verkliga livet.

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Abstract

Wireless Sensor Networks are often deployed in great numbers spanning large, sometimes hard to reach and hostile, areas with the aim of monitoring environmental conditions through the use of different sensors. Due to decreasing costs of ownership (e.g. non-proprietary protocols), recent advances in processor, radio, and memory technologies and the engineering of increasingly smaller sensing devices, the availability and area of application for wireless sensor networks have steadily been increasing.

Sigma Technology Development Stockholm AB raised the question as to whether a wireless sensor network, running an open-source operating system and communicating over IPv6, could be used in the field of smart autonomous irrigation? The company also required a proof-of-concept system for demonstration purposes and to identify if the design choices made were suitable for an actual implementation.

There are numerous of design decisions that have to be made when constructing an irrigation system: the back-end set-up, which irrigation algorithms to use, what hardware to choose and how to communicate? This thesis therefore focuses on the overall system design of a wireless sensor network in the field of irrigation and highlights the trade-offs being made and their pros and cons.

Two improvements related to the existing technology and the proof-of-concept system are presented in this thesis. Firstly, the recommendation to use clustered self-healing routing despite claimed power consumption issues. Secondly, a new technique to minimize power consumption, by dynamically changing the sleep interval on the sensor nodes with the help of weather data. Furthermore, the proof-of-concept system is constructed and analysed to assess whether the system design choices made are valid for a real-life deployment.

Acknowledgements

This master thesis has been conducted together with Development Stockholm AB, a part of Sigma Technology, Sweden.

We would like to thank Development Stockholm AB for making this thesis possible, and our industry supervisor, Daniel Thysell, for his know-how, enthusiasm and willingness to part with said know-how.

From KTH we would like to thank our supervisor, Sagar Behere, for thorough and continuous feedback and a kick in the behind when needed.

We would also like to thank each other for the support and camaraderie that has been the trademark of our time working together.

Last but not least we would like to thank our family and friends for bearing with us through the less pleasurable episodes of this thesis. Your love and support helped us pull through.

Johanna Simonsson and Kim Öberg
Stockholm, June 2014

Glossary

6LoWPAN 6LoWPAN is an acronym of IPv6 over Low power Wireless Personal Area Networks. 1

ADV ADV is a advertisement message broadcasted by the self-elected cluster heads when advertising their status to the neighbouring nodes. 19

BLIP The Berkeley Low-power IP stack is an implementation in TinyOS of a number of IP-based protocols. 46

CCA A Clear Channel Assessment is when the physical layer of the IEEE 802.15.4 checks whether the communication channel is occupied by a transmission or not. 40

CH In hierarchical cluster-based routing schemes, so called cluster heads (CHs) are elected as data aggregators and forwarders for the surrounding nodes within a certain radius. This in order to effectively balance and reduce the energy consumption of the network. 31

Contiki Contiki is an open source operating system for networked, memory-constrained systems with a particular focus on low-power wireless Internet of Things devices. 46

COOJA COOJA is a network simulator for Contiki systems. 28

CoRE Constrained Restful Environments is one out of three IETF (Internet Engineering Task Force) working groups, all with the aim of producing a nonproprietary solution, interoperable with the most widely used protocols of the Internet, IP, the Internet Protocol. 38

DAG Directed Acyclic Graphs define a tree-like structure that specifies the default routes between different nodes within a WSN. 43

DFS Dynamic Frequency Scaling is a technique where the frequency on an MCU is dynamically changed to reduce power usage or heat dissipation. 37

DODAG Destination-Oriented Directed Acyclic Graphs is a version of DAGs in which the sink nodes or Internet-gateways act as the roots of the DAGs. 43

DT Direct Transmission is a routing scheme in which the sensor nodes communicate directly with the sink node. 28

EECS The Energy Efficient Clustering Scheme is a routing scheme for WSNs which elects cluster heads based on residual energy through local radio communication. 34

ET Evapotranspiration is the sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere. 7

FND First Node Dies is a common measurement of the lifespan of a WSN. If used it means that the system is considered dead when the first node dies. Common other measurements are when 25% or 50% of the nodes have died. 19

HEED Hybrid Energy-Efficient Distributed clustering periodically selects cluster heads (CHs) according to a hybrid of the node residual energy and a secondary parameter, such as node proximity to its neighbors or node degree. 34

IEEE The Institute of Electrical and Electronics Engineers (IEEE) is a professional association with its corporate office in New York City. It was formed in 1963 from the amalgamation of the American Institute of Electrical Engineers and the Institute of Radio Engineers. Today it is the world's largest association of technical professionals and the objectives are the educational and technical advancement of electrical and electronic engineering, telecommunications, computer engineering and allied disciplines. 38

IETF Internet Engineering Task Force develops and promotes standards that relates to the Internet protocol suite (TCP/IP). 38

Internet of Things The term Internet of Things refers to the interconnection of uniquely identifiable embedded computing-like devices within the existing Internet infrastructure. Typically, IoT is expected to offer advanced connectivity of devices, systems, and services that goes beyond machine-to-machine communications (M2M) and covers a variety of protocols, domains, and applications. 1

IoT The term Internet of Things refers to the interconnection of uniquely identifiable embedded computing-like devices within the existing Internet infrastructure. Typically, IoT is expected to offer advanced connectivity of devices, systems, and services that goes beyond machine-to-machine communications (M2M) and covers a variety of protocols, domains, and applications. 46

IP The Internet Protocol is the communications protocol which is used on the Internet, and suite for routing datagrams across network boundaries. 38

IPv4 IPv4 is the dominant internetworking protocol in the Internet Layer today. 41

IPv6 IPv6 is the successor to IPv4, the main difference being the addressing system, IPv4 uses 32-bit addresses (translates to $4.3e9$ unique address) while IPv6 uses 128 bit addresses ($3.4e38$ unique addresses). 38

LEACH Low-Energy Adaptive Clustering Hierarchy is a cluster-based hierarchical routing protocol which employs adaptive cluster head rotation. This means that instead of forming clusters with static cluster heads, the role of being the cluster head is rotated among the nodes each round of transmission. Each round consists of two phases, the set-up phase and the steady-state phase. 18

LLN Low Power and Lossy Networks is a sub-category of the WSN family with high packet loss and link loss as characteristics. 38

LR-WPAN A Low-Rate Wireless Personal Area Network is a wireless computer network used for low-rate data transmission among devices such as computers, telephones and personal digital assistants. 41

MAC The media access control layer of the OSI model. 39

MAD The threshold when a plant becomes stressed is referred to as MAD, or Maximum Allowable Depletion, which is expressed as a percentage of θ_{ac}. A common MAD is around 50%. 9

MCOP Multi-Criterion Optimization or Multi-Objective Decision making is an engineering design method that deals with problems that have several conflicting and possibly non-commensurable criteria which should be simultaneously optimized. 31

MCU A microcontroller unit is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. 20

MOECS Multi-Criterion Energy Consumption Optimization is a clustering scheme developed by [59]. 32

MTU The Maximum Transmission Unit of a communications protocol of a layer is the size (in bytes) of the largest protocol data unit that the layer can pass onwards. 41

OSI The Open Systems Interconnection model (OSI) is a conceptual model that characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers. 38

PAN A Wireless Personal Area Network is a wireless computer network used for data transmission among devices such as computers, telephones and personal digital assistants. 39, 41

PHY The physical layer of the OSI model. 39

ROLL Routing Over Low Power and Lossy Networks is one out of three IETF (Internet Engineering Task Force) working groups, all with the aim of producing a nonproprietary solution, interoperable with the most widely used protocols of the Internet, IP, the Internet Protocol. 38

RPL Routing Protocol for Low-Power and Lossy Networks, pronounced "Ripple", is a routing protocol developed by the IETF ROLL working group. 42

sensor node A sensor node, also known as a mote, is a node in a wireless sensor network (WSN) that is capable of performing some processing, gathering sensory information and communicating with other connected nodes in the network. 3

TCP Transmission Control Protocol is a transport layer protocol and the standard for the internet protocol stack. It is used when reliable and ordered communication is needed. The services include errorchecked delivery, flow control and connection-oriented communication through handshaking. 40

TinyOS TinyOS is a free and open source software component-based operating system and platform targeting wireless sensor networks (WSNs). TinyOS is an embedded operating system written in the nesC programming language as a set of cooperating tasks and processes. 46

TOSSIM TOSSIM is a network simulator for TinyOS systems. 28

UDP User Datagram Protocol is less complex than TCP, and focuses on transmission rather than security. This means no handshaking or such, which means UDP cannot ensure delivery or avoid duplication. 40

uIP | micro IP The uIP was an open source TCP/IP stack capable of being used with tiny 8- and 16-bit microcontrollers. It was initially developed by Adam Dunkels of the "Networked Embedded Systems" group at the Swedish Institute of Computer Science. In October 2008, Cisco, Atmel, and SICS announced a fully compliant IPv6 extension to uIP, called uIPv6. 46

WSN A wireless sensor network, known as a WSN, consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. The more modern networks are bi-directional, also enabling control of sensor activity. 1

ZigBee ZigBee is a specification for a suite of high-level communication protocols used to create personal area networks built from small, low-power digital radios. ZigBee is based on an IEEE 802.15 standard. 39

Contents

1 Introduction

This report is the result of a Master Thesis carried out in the spring of 2014 by Johanna Simonsson and Kim Öberg with the Department of Machine Design at the Royal Institute of Technology, Stockholm, in collaboration with the company Sigma Technology Development Stockholm AB.

This introduction chapter will outline the background for said thesis, the problem definition, hypothesis, scope, methodology and literature sources.

1.1 Background

Wireless Sensor Networks, *WSNs*, are often deployed in great numbers spanning large, sometimes hard to reach and hostile, areas with the aim of monitoring environmental conditions through the use of different sensors. Due to decreasing costs of ownership (e.g. non-proprietary protocols), recent advances in processor, radio, and memory technologies and the engineering of increasingly smaller sensing devices, the availability and area of application for WSN nodes have steadily been increasing. [1, 2, 3]

Sigma Technology Development Stockholm AB, henceforth known as *the company*, raised the question as to whether a WSN, running an open-source operating system and communicating over 6LoWPAN protocol, could be used in the field of autonomous irrigation? 6LoWPAN was chosen because of the company's profile within Internet of Things and embedded software. Subsequently there was a need to answer whether there existed a need for such a solution. The company also required a proof-of-concept system for demonstration purposes and to identify if the design choices made were suitable for an actual implementation. To answer these questions and to be able to develop the proof-of-concept system, one needs to know more about autonomous irrigation.

Autonomous, or 'smart', irrigation has steadily been gaining momentum in recent years, and the advantages are many: less manpower needed, lower risk for over or under watering, possible reduction in water usage in water constrained areas and so on. The different ways in which autonomous irrigation is implemented can be divided into two categories: weather and soil moisture sensor-based.

The weather-based application can be summarized as monitoring weather conditions, either via sensors (rain, wind, light etc.) or by gathering data from one or more online weather services. The needed irrigation is then estimated with help of a series of equations. The problems with this solution are [4]:

a) the local environmental variations cannot be observed or compensated for since weather data represents an average value usually spanning a large area.
b) no feedback on how much water is actually dispersed.

With the other approach, soil moisture sensors are deployed scarcely throughout the area and will trigger an irrigation-interrupt when the moisture level sinks below a pre-programmed threshold value. The problems with this solution are [4]:

a) the local environmental variations cannot be observed or compensated for since there are too few sensors leading to a sparse monitoring.
b) it's a reactive system, meaning it cannot model and/or adjust future irrigation.

What's interesting is the fact that neither of the irrigation systems mentioned above, which are currently on the market, utilize WSN technology. However, WSN technology have been gaining momentum in the field of precision agriculture, which refers to agriculture in which small fluctuations in the micro-climate (crop specific) are accounted for when irrigating, harvesting, seeding etc. A particular implementation of WSN in precision agriculture is vineyards [5, 6, 7]. The reason for this is simple: certain crops (grapevines) are more exposed to the elements, more sensitive, are grown in a non-uniform environment and therefore require closer monitoring. The WSN technology, in comparison to regular weather station monitoring, offers precisely that: a more dense and local observation resulting in more data and more location specific data, which can be used to closely monitor all required areas of the vineyard, making sure they are all equally attended to.

Furthermore, [8] states that with the help of precision monitoring of soil moisture content utilizing a WSN, one can optimize irrigation by minimizing the water usage and energy waste. By doing so and making sure that the crop receive the exact amount of water they need, the outcome will be increased crop yield. However, none of the reviewed market leading products utilize this technology [4]. The aim is therefore to design for this found gap in the market. The missing knowledge will be obtained by studying the precision agriculture applications.

Out of the reviewed work within precision agriculture, none have put much (if any) effort into power optimizing the actual WSN [6, 7, 5, 9]. The authors in [7] for example, simply concluded that the nodes carrying most of the data traffic only stayed active for 6 weeks at a time (on 42 amp hours of battery power). Since the period from seeding to harvest season for many crops goes on for ~ 6 months, 6 weeks is far from sufficient.

Furthermore, the important trade-off constantly being made in the research is that between power consumption and robustness. Instead of investing in a smart, robust, self-healing routing scheme (which would supposedly cost too much energy) network schemes with static routing tables are chosen, resulting in unstable networks where link loss and packet loss rates are high.

Beyond this there are numerous of design decisions that have to be made when constructing an irrigation system: the back-end set-up, which irrigation algorithms to use, what hardware to choose and how to communicate? Therefore, this thesis will focus on the overall system design of a WSN in the field of irrigation and highlight the trade-offs being made, their pros and cons and suggest improvements to the existing technology.

1.2 Problem definition

One of the problems in today's autonomous irrigation is the need for assumptions of heterogeneity. In order to irrigate a field, based on weather data or scarcely distributed sensors, one has to either assume that the entire field is completely homogeneous, i.e. that no differences in soil, elevation, root depth or irrigation needs exist, or use assumptions of heterogeneity (which are left unconfirmed).

However, irrigated fields are not homogeneous and assumptions of heterogeneity is not enough. But up until recently it was believed that the differences were small enough to be negligible. Precision agriculture, via dense monitoring, has changed that. With the data that is now being gathered the knowledge of the system increases. This makes it easier to take the decisions regarding irrigation, and therefore optimizing the water usage. This results in both increased crop yield and productivity. [10]

Of the reviewed systems on the market today it is concluded that dense monitoring systems do exists but they are not aimed at irrigation. Therefore this thesis aims to answer the following questions:

1. *How to design a WSN-based, smart irrigation system with dense monitoring?*

2. *Which are the system design decisions that are the most relevant?*

1.3 Hypothesis

Simultaneously, while conducting the background study, a couple of hypotheses were developed, connecting back to the research questions mentioned in Section 1.2. These hypotheses are presented below.

1. The company had previous experience within constructing WSN systems and together with knowledge gathered during the background research it was hypothesized that:
   A suitable setup for an irrigation system consists of: sensor nodes, soil moisture sensors, one sink node and a main frame functioning as back-end.

2. During the background research it became obvious that weather data was only being used to predict irrigation needs, not power manage the system. It was therefore hypothesized that:
   Weather data can be used to lower power consumption.

3. Few reviewed systems used feedback despite its known advantages [11] and it was therefore hypothesized that:
   A feedback system could improve the performance of the system.

4. The reviewed research showed lack in advancements in this area of utilizing self-healing, robust networks due to focus lying elsewhere (agricultural significance, coverage, ease of installation, data accumulation etc), so it was hypothesized that:
   The routing scheme can be self-healing and robust without drawing too much power.

5. After having analysed existing solutions and research, in which most focus on power modes handling and/or network lifetime it was hypothesized that:
   The most important design decisions related to power management are power modes handling and network setup.

1.4 Scope and limitations

Irrigation and agriculture as a disciplines are complex and demand the knowledge and expertise of geologist, biologists and ethnographers, not just embedded software developers [5]. That, together with the fact that this is a Master Thesis with the Department of Machine Design, the focus naturally shifts towards the Mechatronic design decisions of the irrigation system. Therefore, the focus will be on gaining knowledge in a variety of areas (see bullet list below) so that the system design choices are well motivated and based on the conducted research.
The field of study will consist of:

- Wireless sensor networks
  - Node deployment
  - Network topology
  - Routing protocols
  - Power management on node level
- Basic irrigation techniques
- Smart/Autonomous irrigation
- Precision agriculture

Since this is a master thesis within the Mechatronic discipline, the choices regarding water distribution hardware and irrigation decisions will not be focused on. Consequently the following areas will not be included in the scope:

- Hardware control (e.g pumps and valves)
- Water distribution (e.g sprinklers and drip irrigation)
- Irrigation calculations and decisions

As the company raised the question mentioned in Section 1.1 they also asked for a proof-of-concept system, with the purpose of investigating whether the design choices made are suitable for an actual implementation. The scope for the proof-of-concept system will thereby include the following:

- Software and hardware decisions regarding sensor nodes and soil moisture sensors.
- Software decision for the back-end.
- Use of weather data when power managing the system.
- Construction of a feedback irrigation system.
- Routing choice for the network and its implications.

And subsequently the following falls outside of the scope:

- Hardware decisions for the back-end (company computers are pre-determined).
- User interface. No user interface will be implemented on the main frame, its only task is to collect, store and perform computations on data.
- Irrigation, i.e. no connections to hardware like pumps, valves and so forth will be considered.
- Irrigation calculations, i.e. the back-end will conclude whether irrigation is needed based on collected data but will not calculate the exact amount since that would require an actual physical test bed. An exact irrigation algorithm also requires in-depth knowledge of the deployment area.
- Hardware robustness choices corresponding to an actual deployment.
- To build routing protocols from scratch, but rather implement already existing solutions to see if they are suitable.

The scope presented in this Section was not the initial one. The previous scope and reasons for the switch is presented in Appendix A.

1.5 Methodology

Since this thesis will focus on design decisions and thereby flaws and possible improvements in existing technology the methodology will be of an investigative nature. A thorough background study will be conducted, outlining the existing market and which aspects of the autonomous irrigation systems could benefit from improvement. In order to determine this, thorough research into the different architectural, hardware and software aspects of the system has to be made. Only by knowing what is considered State of the Art within WSN technology, soil sensors, network algorithms, power management, robust networking and so forth, can the room for improvement be identified.

Once this gap in market and possible improvements have been identified, indicative analytical calculations and estimations will be performed to determine which approaches should be looked into further and which design choices are the most important. In short, which suggestions are viable as possible improvements.

To validate the chosen design decisions a proof-of-concept system will be constructed. The aim is to determine whether the chosen hardware, software and system design approaches are suitable for actual deployment.

Lastly, an evaluation of said proof-of-concept system will be made, with the aim to identify possible room for improvement.

1.6 Literature sources

When the research for this thesis was conducted, the following guidelines were followed:

- If possible, use primary sources instead of secondary, since they include first-hand research and experiences, while secondary resources rely heavily on the research and experiences of others.
- Try to find sources of different kinds: books, scientific journals and articles, internet searches and newspapers.
- Utilize the sources mentioned in the chosen articles, journals, books etc as these are often primary ones.
- Make sure the research is relevant and up to date.
- Try to find articles from peer-reviewed journals, since they will not publish articles that fail to meet the standards established for a given discipline. Peer-reviewed articles that are accepted for publication exemplify the best research practices in a field. [12]

Because of these guidelines the online library at KTH (KTHB Primo) and Google Scholar were primarily used for collecting peer-reviewed state of the art material. KTHB Primo particularly has the feature to only show peer-reviewed material. For these searches the following keywords were used in different combinations:

- wireless sensor network
- precision agriculture/irrigation
- smart irrigation systems
- power efficient
- network power optimization

The list of keywords were then iterated after each completed search, sometimes they were narrowed down (*power efficient hierarchical routing protocols*) and sometimes made more generic (*embedded system power management*). Several internet searches were also conducted with the use of the same keywords, particularly the mapping of the existing market for irrigation systems.

1.7 Report outline

The report is organized in the chapters as follows.

1. **Introduction:** Outlines the background for the thesis as well as problem definition, hypothesis, scope, methodology and literature sources.
2. **Theory:** Goes through the theoretical background of the core concepts in the thesis to establish a basic understanding and a context for the State of the Art chapter.
3. **State of the Art:** Aims to cover what is considered *State of the Art* in WSN technology and irrigation system design.
4. **Method:** Describes the requirements, system design and component choices for the engineering task of the Master Thesis.
5. **Implementation:** Describes the proof-of-concept system, a result of the design choices made in the Method chapter.
6. **Analysis**: Analyses and evaluates the chosen approaches in the Method and Implementation chapters. Identifies possible room for improvement.
7. **Results:** Presents the resulting proof-of-concept system and relates back to the initial requirements.
8. **Discussion:** Discusses the background study (SoTA), proof-of-concept system and Analysis. Evaluates and lays the foundation for the Future work chapter..
9. **Future Work:** Presents possible future implementations and improvements based on the findings in the thesis.
10. **Conclusion:** Reviews the main findings of the thesis in a summarizing form.

2 Theory

This chapter will go through the theoretical background of the core concepts in the thesis, namely irrigation systems, system design, power consumption models and low power wireless sensor network characteristics. The aim is to establish a basic understanding and a context for the following State of the Art presented in Chapter 3.

2.1 Irrigation

This section is written to gain a deeper understanding on how irrigation works and what parameters affect the outcome. Those parameters will be explained further down in Section 2.1.1 and 2.1.2.

The concept of irrigation is for the appropriate quantity of water to be applied at the right time [4, p. 3]. To understand how much to irrigate and when, one must take a few variables into consideration (see bullet list below), as both over and under irrigation can be harmful for the plants and the ecosystem in the nearby area.

- **Weather conditions**: temperature, rainfall, humidity, wind, and solar radiation.
- **Plant types**: low versus high water use and root depth.
- **Site conditions**: latitude, soils, ground slope and shade. [4, p.7]

The summarized need for irrigation is expressed in the soil water balance equation:

$$I = R - ET_C \pm \Delta\theta \pm \Delta SF - RO - DP + CR, \tag{2.1}$$

where I is the needed irrigation, R the rain content, ET_C the calculated evapotranspiration constant, $\Delta\theta$ the change in soil water content, SF the surface flow,RO the surface run-off, DP the deep percolation and CR the capillary rise [13]. The unit of I is expressed as water change per time unit, $[mm/day]$.

In reality however, SF can often be ignored except when growing on large slopes. The last three variables CR, RO and DP are difficult to estimate in the field. CR is often zero, and the other two can be accounted for in $\Delta\theta$ [14]. These assumptions can be summarized in the equation

$$I = R - ET_C + \Delta\theta. \tag{2.2}$$

The soil water content $\Delta\theta$ and evapotranspiration ET_C will be presented in Section 2.1.1 and 2.1.2.

2.1.1 Soil water content

The soil water content is a way to express how much water is available for the plant. To calculate this variable, the soil texture needs to be studied. Plants are grown in inorganic soil, which mainly consists of fragments of rocks and minerals, compared to organic soils which consists of plant remains and other organic leavings (often used as fertilizer). Inorganic soil is denoted as a combined mix of silts, sands and clay. The soil is classified based on its composition and subsequent qualities, see Figure 2.1.

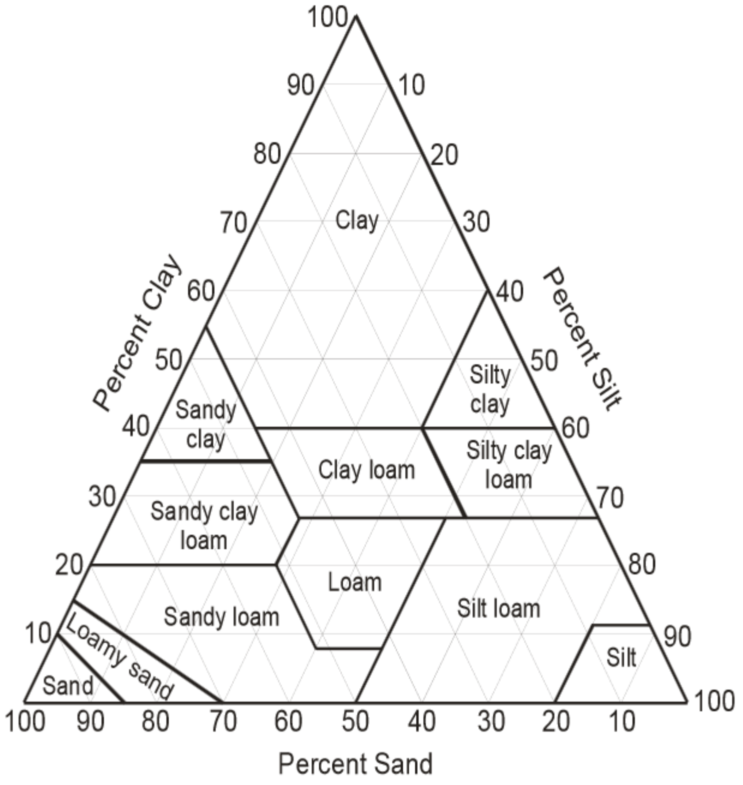


Figure 2.1: Depending on the percentage of sand, silt and clay, the different soil texture classes are formed. [15]

The level of porosity in the soil is directly dependent on the soil composition. Porosity, or void fraction, is here defined as a measure of the void (i.e., "empty") spaces in the soil, through which the water can work its way down into the ground. The level of porosity influences the possibility for plants to transpire water from their roots, and these hydro-logic properties are measured in soil water content. The soil water content θ can be expressed as:

$$\theta = \frac{V_w}{V_{tot}} \tag{2.3}$$

where V_w is the total volume of water and V_{tot} is the total volume of air, water and soil under the surface. There are three levels of soil water content (θ) that are relevant to irrigation, and their values are all dependant on which soil composition is used. The first one is θ_{PW}, the permanent wilting point. At this level the plant can no longer extract water from the soil. As the name suggests, the plant will, in the worst case scenario, wilt. The second one is the θ_{FC}, which stands for field capacity. This is the threshold at which the gravity starts to influence the water, overcoming the capillary forces in the soil and starting to drag the water down. If this happens, unnecessary water and nutrients will be lost. The last one is θ_{ac}, the available water content for the plant, and spans between θ_{PW} and θ_{FC}. The relationship between the three variables can be expressed as:

$$\theta_{PW} < \theta_{ac} < \theta_{FC}. \tag{2.4}$$

However, this expression is not enough to define the minimum limit of water a plant needs, as plants can become stressed. A plant is stressed when it has to force itself to absorb water from the soil, with consequences like insufficient growth and crop yield. The threshold when a plant becomes stressed is referred to as *MAD*, or Maximum Allowable Depletion, which is expressed as a percentage of θ_{ac}. A common MAD is around 50%. Therefore, when irrigating plants, the water level needs to stay in the interval called soil moisture target, θ_{target}, where

$$\theta_{MAD} < \theta_{target} < \theta_{FC}. \tag{2.5}$$

The job of the irrigation scheduler is to make sure that the soil moisture stays within these thresholds, see the marked area in Figure 2.2.

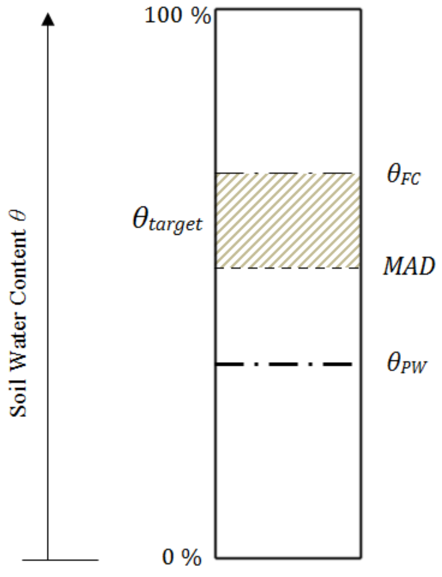


Figure 2.2: Display of the soil water target θ_{target} in relation to Field Capacity θ_{FC}, Permanent Wilting Point θ_{PW} and Maximum Allowable Depletion, MAD.

2.1.2 Evapotranspiration

Evapotranspiration is defined as the combination of normal water evaporation and the process of water movement through a plant and its evaporation from aerial parts (plant transpiration) [13].

Expressed in water loss per time unit it is referred to as the evapotranspiration rate ET and is often measured in millimetre per day, $[mm/day]$. A standardized way to calculate ET_0 is made in [13], and is widely recognized as the best way to estimate ET [4]. It consists of an equation, referred to as the Penmann-Monteith equation, and is expressed in the following way [13]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2.6}$$

where

ET_0: reference evapotranspiration rate $[mm/day]$
R_n: net radiation at the crop surface $[MJ/m^2/day]$
G: soil heat flux density $[MJm^{-2}day^{-1}]$
T: mean daily air temperature at 2 m height $°C$
$e_s - e_a$: saturation vapour pressure deficit $[kPa]$
Δ: slope vapout pressure curve $[kPa°C^{-1}]$
γ: psychometric constant $[kPa°C^{-1}]$

Further analysis on how to calculate each of the variables can be found in [13].

However, irrigation requirements differ between crops, soil and location and the same is true for the evapotranspiration rate. To obtain an ET value for a specific crop, one must modify ET_0. ET_0 is the empirically derived constant evapotranspiration rate for grass. By multiplying it with a constant K_C, as seen in equation

$$ET_C = K_C \cdot ET_0, \tag{2.7}$$

one can obtain the correct value for a certain crop. K_c is directly dependent on what type of crop is being grown, and what growth stage the crop resides in. Details about K_c and different values can be found in [13, chap. 6].

In order to further discuss and elaborate on the calculation of ET_0 a proposed simplification of Equation (2.6) will be used. Hargreaves and Samani [15] proposed the following equation for calculating ET_0:

$$ET_0 = 0.0023\ R_A\ (T + 17.8)\ \sqrt{TR} \tag{2.8}$$

where R_A is extraterrestrial solar radiation, T is the mean air temperature in $°C$ and TR is the average daily temperature range for the considered time period. Since TR is influenced by solar radiation, local advective energy and abrupt weather changes (storms), the equation will not be accurate on days with large weather changes but it has been proven to deliver satisfactory results when T and TR are averaged over periods of five or more days [15].

The extraterrestrial solar radiation is computed with the following equation:

$$R_A = 37.6\ d_r(\omega_s\ sin\,\phi\ sin\,\delta + cos\,\phi\ cos\,\delta\ sin\,\omega_s) \tag{2.9}$$

where R_A is in units of $MJ/m^2/day$, d_r is the relative distance from the earth to the sun, ω_s is the sunset hour angle (rad), ϕ is the latitude (rad) and δ the declination of the sun (rad) [15] and they are defined as:

$$\delta = 0.4093 sin\ \frac{2\pi(284 + J)}{365} \tag{2.10}$$

$$d_r = 1 + 0.033\ cos\left(\frac{2\pi J}{365}\right) \tag{2.11}$$

$$\omega_s = cos^{-1}(-tan\,\phi\ tan\,\delta) \tag{2.12}$$

where J is the calendar day (1-365).

Once the value of ET_0 has been calculated the choice of K_c can be made. K_c is directly dependent on what type of crop that is grown, and what growth stage the crop resides in. Details about K_c and different values can be found in [13, chap. 6].

Example calculation of R_A:
For $27°N$ latitude ($\phi = 0.4712\ rad$) on January 8th, the value of δ is -0.3893, d_r is 1.0327 and ω_s is 1.3602. From Equation (2.9) the value of R_A is 22.20 $MJ/m^2/day$.

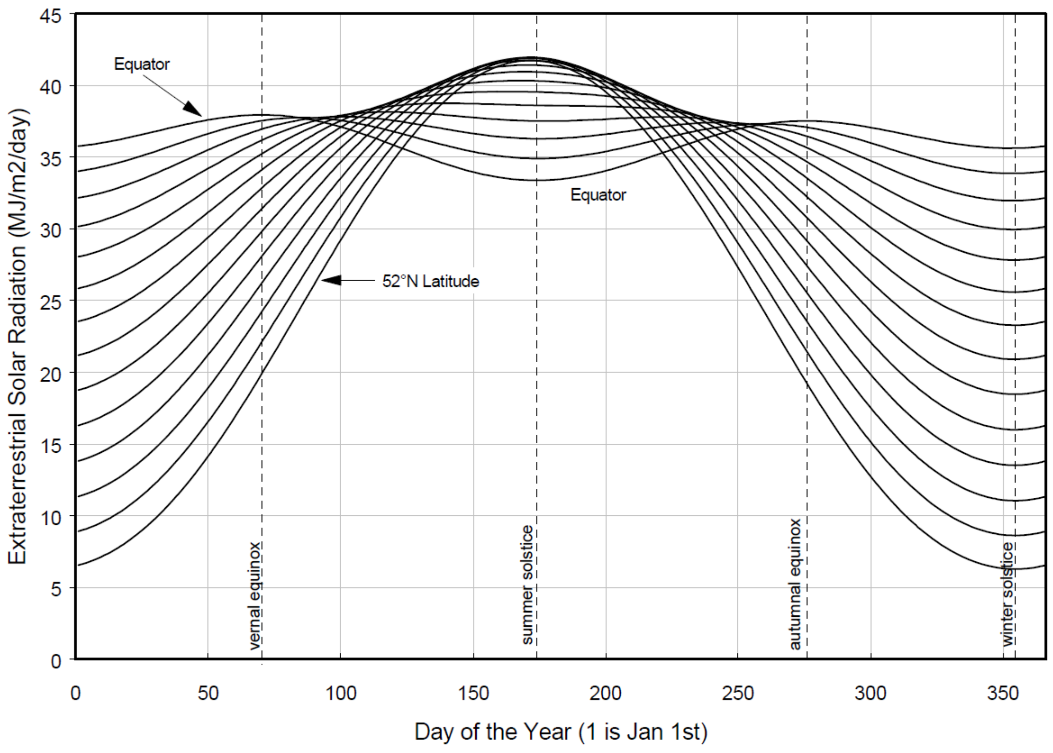


Figure 2.3: Curves of R_A in $MJ/m^2/day$ for northern latitudes 0° to 55° with 4° increments. [15]

As can be seen in Figure 2.3 there is a relatively high annual variation in extraterrestrial solar radiation at the higher latitudes, whereas the variation at the equator is minimal. This leads to the conclusion that year-round cropping is a possibility at low latitudes, particularly within the tropics (23.5°N and °S) [15].

2.2 Characteristics of wireless sensor networks

When constructing an autonomous irrigation system, power management will inevitably play a part of any successful installation. One of the most influential parameters on power consumption in WSNs is the routing scheme, as a poorly chosen one will cause the nodes' radio to idle listen when not necessary and perhaps forward packages along sub-optimal routes to the sink, causing unnecessary battery depletion in the process.

This section will outline the major design decisions that have to be made when designing an autonomous irrigation system based on WSN technology. It will also highlight the different parameters for which optimization can be made.

2.2.1 System dynamics

When constructing a wireless sensor network with the subsequent topology choices and routing schemes it is important to first conclude which type of system it will be applied on. Systems are often categorized into proactive and reactive. Proactive systems are defined by long sleep periods and pre-scheduled intermittent wake-ups, upon which all nodes either collect sensor data and/or forward data to the base station. This kind of system is very well suited for implementations such as habitat monitoring, intelligent buildings and precision agriculture, to mention a few. [16, 17]

Contrary to proactive systems, reactive systems sleep less and are pinged for sensor data upon user's request or if there's a critical change in the network field. Such a network is aptly built for battlefield and machine surveillance, earth movement detection, wild animal monitoring and industrial applications, among others. [17]

However, not all implementations of a wireless sensor network are strictly proactive or reactive, combination systems exist and are referred to as hybrid systems. For a complete set of distinguishing characteristics of the two systems see Table I.

Table I: Characteristics of proactive and reactive networks [16].

Description	**Proactive**	**Reactive**
Application type	Periodic monitoring	Critical monitoring/Event detection
Mode of sensing circuitry	Periodically switch on	Always on
Mode of communication device	Periodic switch on	Always on
Data delivery	Periodic/continous	Event driven/On demand

Seeing as this thesis concerns a system which is to be deployed in an agricultural context, it can be concluded that the system should be categorized as proactive. The aim is for the nodes to only wake up and/or do sensor readings when absolutely necessary and go into idle or sleep mode in between those events. Furthermore, monitoring of crops is a slow process even when talking about "rapid" weather changes (an approaching cold front can take up to 6 hours to arrive [5]) and therefore no reactive system characteristics are needed.

2.2.2 Deployment of nodes

Another important factor, when deciding on a routing protocol, is whether the nodes will be randomly or deterministically deployed. Deployed in this context refers to how to nodes are physically placed in the monitored area. Deterministic deployment has many advantages, such as: even node distribution within the network area, less interference and less unnecessary overlap in coverage.

However, deterministic deployment is only possible when the area is easily accessible, for hostile and unreachable areas random deployment is the only option. As a result, a larger quantity of nodes are required to make sure that, despite the uneven distribution, the entire area of interest is covered. This however, in turn, leads to a higher probability of two nodes overlapping, and thereby registering the same data, often referred to as data redundancy, see Figure 2.4. [16]

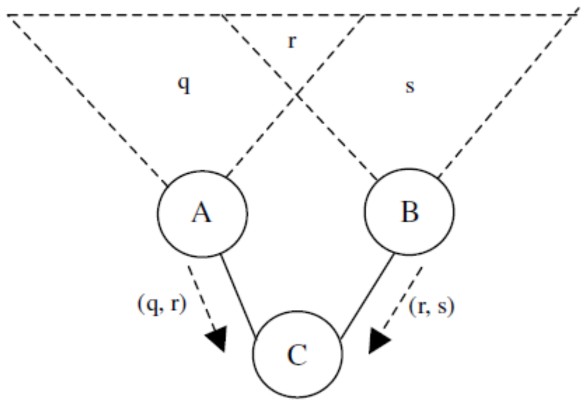


Figure 2.4: The data redundancy issue. Node A and B overlap and will both be reporting sensor data regarding area r to the sink node C. [18]

In the field of agriculture and irrigation, it is most likely that deterministic deployment will be used seeing as the monitored area by definition is reachable since it's being used for agricultural purposes and thereby must be possible to harvest.

2.2.3 Network topology

Even though the underlying deployment of nodes might be deterministic the choice of network topology can still vary greatly. The term network topology here refers to how nodes are deployed, related and connected to each other within the network. The flow of data will therefore be significantly different depending on which topology is chosen (the term includes both hard-wired networks as well as wireless).

There are currently eight different known topologies, and those best suited for wireless implementation are mesh, tree and star network [19, p. 121]. These three will be the topologies studied for the chosen implementation. A good network topology should be able to transfer data back and forth between nodes or to a main computer, and, if scalability is a goal, be able to implement an infinite number of nodes on an infinitely large area.

Mesh topology

The principle of a wireless mesh network is that a node can communicate (transmit data) to any one of its one-hop neighbours, see Figure 2.5. When a message is transmitted from one of the nodes, the other nodes act as routers by forwarding the message to its destination. The goal is often to achieve the shortest route or minimize the number of hops, which can be accomplished by smart algorithms based on the knowledge of the network. This ensures that the hops between the nodes are as few as possible, saving energy and increasing the speed. A central server for computation may or may not be implemented, depending on the implementation. [20]

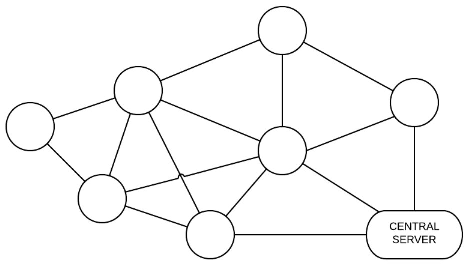


Figure 2.5: Mesh network where a node is connected to its closest neighbours, and a central server is implemented.

In short, a mesh topology has the following advantages and disadvantages:

+ Can find new routing paths when neighbouring nodes break down (self-healing).
+ It's easy to find and isolate faults.
+ Scalable due to multi-hop architecture.
− Installation and reconfiguration of nodes is rather advanced compared to static routing table networks,

  ⇒ adding new sensor nodes spawns a substantial amount of message overhead when establishing new routes for the added and neighbouring nodes.

Star topology

The main node in a wireless star network is the central one, which can be seen as a hub, see Figure 2.6. The peripheral nodes communicate with each other through the hub, which amplifies and forwards the message to its destination. The hub can be active, which means that the message will be evaluated before its forwarded, or passive, where the message is only passed on. [21]

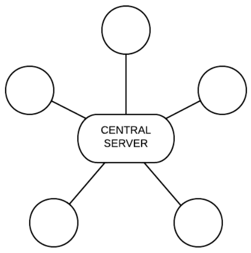


Figure 2.6: Star network topology with a central server as hub.

In short, a star topology has the following advantages and disadvantages:

+ The data only needs to pass through a finite number of nodes.
+ Energy-efficient.
+ Scalable.
+ Installation and reconfiguration of nodes is easy.
− The maximum area are dependent on the maximum reach of the antennas in the nodes.

Tree topology

The tree structure is a hierarchical topology which begins with a root node. From this root node the tree branches out to leaves, the number dependent on the branching factor f, see Figure 2.7. If $f = 1$, the topology is linear, where as if $f = n$, each node can have up to n leaves branching out. The nodes communicate with each other through point-to-point links. The central server, which evaluates the data, is the root node. The main branches from the root is called backbone, and is where most of the information will travel. [22]

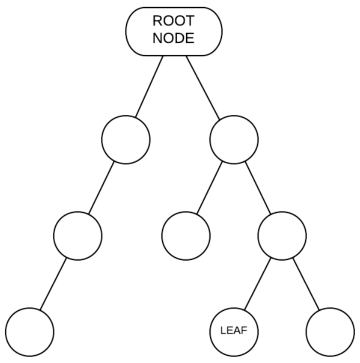


Figure 2.7: Network topology of a tree structure with branching factor $f = 2$.

In short, a tree topology has the following advantages and disadvantages:

+ Flow of data is easy to follow.
+ Scalable.
– Dependant on backbone branch.
– Connection between nodes needs to be predefined.

2.2.4 Routing

On top of these topologies a routing scheme is chosen. Which routing protocol the network employs is tightly linked to the chosen network topology but not inherently dependent thereof. Network topology will therefore be abstracted away from the following section in order to focus on the specific algorithms for routing.

Sensor nodes are constrained in bandwidth, often deployed over large, sometimes hard to reach, areas and required to operate, for long periods of time, disconnected from the power grid [18]. These characteristics translate to a number of challenges in the area of energy consumption optimization. In the network layer, of the network protocol stack, the main aim is therefore to construct energy efficient routing and reliable relaying of data without compromising the network lifetime.

The main duties of the network layer is to enable routing and forwarding, others include creating and maintaining a network topology. The two main questions a routing protocol must answer are the following:

- How to provide information for wise forwarding decisions?
- How to organize the forwarding?

A close to optimal solution to these questions would be to utilize a proactive protocol designed to always find the shortest path from sender to destination while simultaneously minimizing the number of hops and the energy consumed. However, such a protocol would require each node to store and keep track of all links in the network, a virtual impossibility when dealing with memory constrained WSN nodes.

In other words, routing in WSNs is a challenge in comparison to ordinary communication and wireless ad-hoc networks because of the following inherent characteristics:

- The flow of data from different areas is directed towards a particular sink node, possibly resulting in traffic congestion, packet collision and bottle necks.
- The sensor data traffic suffers from redundancy issues as several nodes often register the same phenomenon.
- Sensor nodes are constrained in terms of transmission power, energy supplies, processing and memory capacity.

These characteristics have resulted in a number of WSN specific algorithms for routing, which can be categorized into data-centric (flat), hierarchical and location-based protocols [18]. Hierarchical protocols have many advantages, such as better scalability, higher efficiency of data gathering and better capability of load balancing than flat protocols [23]. However, flat protocols are still commonly used and are the base of the hierarchical ones, therefore protocols from both categories will be presented in this section. Location based protocols will not be covered as they are configured with mobile ad hoc networks in mind and therefore not optimized for a static deterministic node deployment within agriculture [24].

2.2.5 Data-centric protocols

Some of the most common and earliest routing protocols for WSNs are the data centric (flat) protocols, among which direct-transmit, flooding and gossiping are the three basic choices [16].

Direct transmission

In small, non-scalable networks, the easiest and most straight forward approach to routing is direct transmission, which means that each node directly transmits its data to the base station, see Figure 2.8.

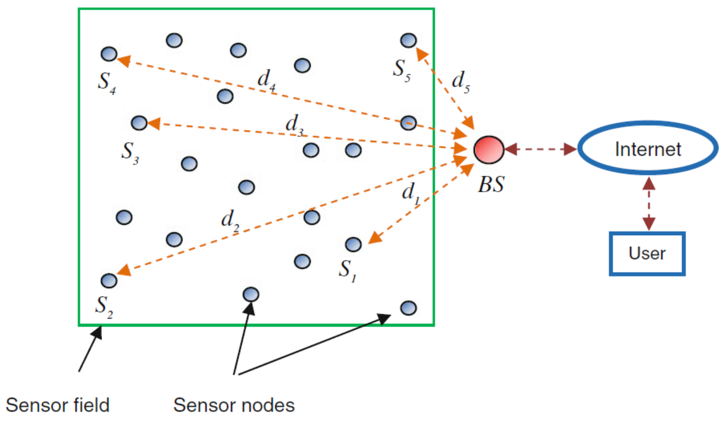


Figure 2.8: Model of direct transmission [16].

To understand the weakness of such a protocol, consider the fact that the farther away nodes are placed from the base station, the more energy (stronger radio signals) will be consumed when transmitting a message. Furthermore, packets travelling long distances will also encounter more obstacles and the risk for packet loss is thereby greater.

When considering this it becomes clear that the nodes farthest away from the base station will die out much quicker, leaving that area of the network unmonitored. Thus, direct transmission is only suitable for the nodes closest to the base station or for very small, non-scalable networks.

As a solution to the issues introduced by direct transmission, short distance travel protocols, such as flooding and gossiping, have been developed. In these multi-hop architectures (see Figure 2.9) all nodes work together by passing on the data to its closest neighbour, thereby reducing the average energy consumed by the far away nodes and thus the overall power consumption of the network. [16]

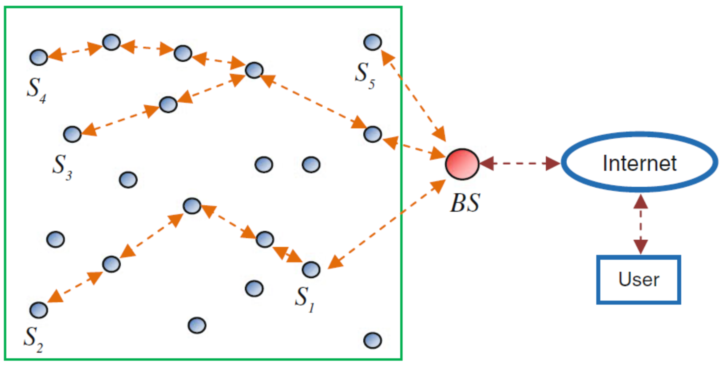


Figure 2.9: Model of multi-hop transmission [16].

Flooding

Flooding works in a broadcasting manner, which means that each node broadcast its data to all neighbouring nodes which then forward the data in the same manner until it reaches the sink node. With this approach no routing tables are needed since all nodes take part in the handling of each data packet. This leads to very low transmission delays but also unnecessary energy usage when all nodes handle every packet transmission in the network. [16]

Another issue introduced by flooding is data implosion, meaning one node receives multiple copies of the same data, see Figure 2.10.

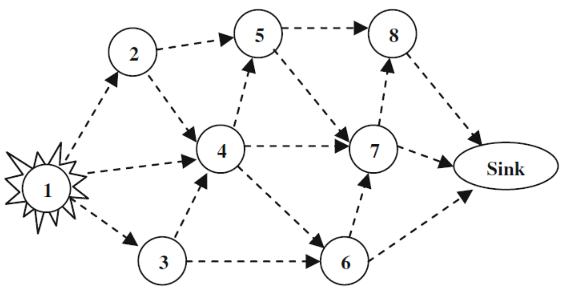


Figure 2.10: Implosion issues in the flooding protocol [16].

As seen in Figure 2.10 above, node 4 will receive multiple copies of the same sensed data since node 1 will forward its data to node 2, 3 and 4 and node 2 and 3 will in turn forward the same data to node 4, 5 and 6. The data is forwarded in the same manner throughout the entire network until it reaches the sink which causes multiple unnecessary transmissions, and thereby energy losses.

Gossiping

Gossiping solves the implosion problem by randomly selecting a neighbour to pass the data to, instead of broadcasting to all nearby nodes. However, this introduces uncertainty as to whether the data packet will actually reach the base station and even if it does, it's very likely to have accumulated quite serious transmission delays along the way. [16]

2.2.6 Hierarchical routing protocols

The point of deploying a hierarchical routing protocol is to ensure that some nodes take responsibility to perform high energy transmissions while the rest perform normal tasks. This becomes particularly important in large scale networks where direct transmission or other flat protocols would dissipate too much energy.

Within the category of hierarchical routing protocols there are two sub-categories: cluster-based and chain-based. In cluster based routing, the nodes are organized in clusters with a cluster head. The cluster head reduces the energy consumption of the cluster by receiving cluster node data and aggregating it before forwarding it to the sink node.

Load balancing is done through a multi-path scheme for data transmission from the cluster head to the base station, meaning data can travel along several different paths on its way to the base station. [23]

The key in chain-based routing however is to form chains among the nodes so that each node will receive and transmit only to one pre-determined one hop-neighbour. Data is thereby aggregated through the chain until it reaches the chain leader which transmits directly to the base station. This way of keeping transmission signals weak (since they only travel short distances) and utilizing data aggregation reduces the average energy spent by each node in the chain. However, since each node in the chain only has one parent node, node failure inevitably leads to packet loss. Adding nodes is also a high energy task as either the whole chain needs to be reconstructed (spawning a large amount of control overhead) or the new node might have to join the chain in a sub-optimal way. Sub-optimal refers to the situation when a node is added to an area in which all other nodes already are a part of the chain (a node can only exist in one unique place in the chain at once) meaning the node will have to connect to another node much farther away, causing long distance high-energy transmissions. [25]

For this reason, the cluster based schemes will be the focus of this section and particularly LEACH which is a popular and well establish protocol [26].

LEACH

LEACH, Low-Energy Adaptive Clustering Hierarchy, is a cluster-based hierarchical routing protocol which employs adaptive cluster head rotation. This means that instead of forming clusters with static cluster heads, the role of being the cluster head is rotated among the nodes each round of transmission. Each round consists of two phases, the set-up phase and the steady-state phase.

In the set-up phase, each node randomly selects a number between 0 and 1, and elects itself cluster head if that number is less than the threshold value $T(n)$ which is computed with the following equation:

$$T(n) = \frac{p}{1 - p(r \cdot mod\frac{1}{p})}, \tag{2.13}$$

where p is the optimal number of cluster heads (estimated at 5% of the total number of nodes), r is the current transmission round and $n \in G$, where G is the set of nodes which have not been cluster heads in the last $\frac{1}{p}$ rounds. [18]

The self-elected cluster heads will then advertise their status to the neighbouring nodes by broadcasting an advertisement message (ADV). The neighbouring nodes will then choose to join the closest cluster head in order to minimize the transmission distance. The choice of which cluster head is the closest is based on which advertisement message is the strongest (all messages are sent at the same transmit energy).

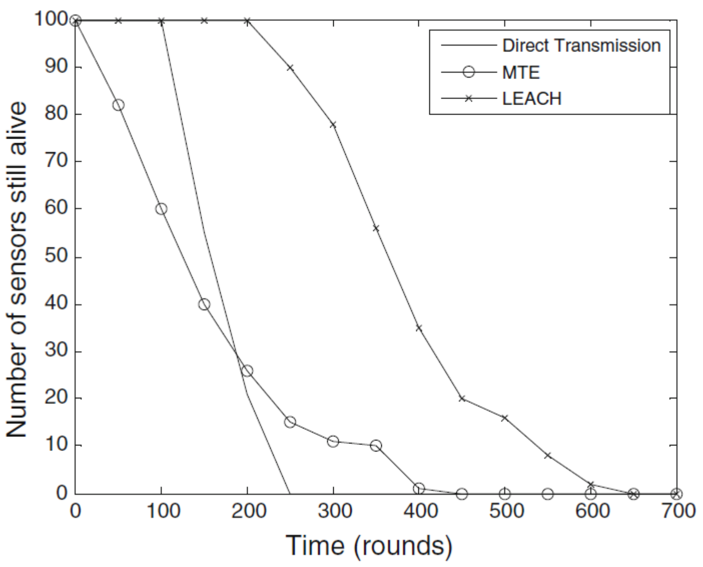


Figure 2.11: Implosion issues in the flooding protocol [16].

When all clusters have formed the steady-state phase begins, in which data from all nodes are forwarded to the base station. After this a new round begins with new clusters and cluster heads. To balance the load among the nodes, a cluster head node is not eligible to become cluster head again within the next $\frac{1}{p}$ rounds. This approach significantly postpones the occurrence of first node dies (FND), thereby prolonging the lifetime of the network. Compared to direct transmission and minimum transmission energy (multi-hop), LEACH is about two times better than the first and four times better than the latter, see Figure 2.11.

However, some issues are introduced by LEACH as well. In the steady-state phase each node in the cluster is awarded a guaranteed time-slot by the cluster head, in which data from the node should be forwarded to the cluster head. This works fine for reasonably sized clusters but since cluster formation in LEACH is fully distributed and requires no global knowledge of the network, clusters are not uniformly sized [18]. This leads to packet losses in oversized clusters since the steady-state duration of one transmission round is fixed for the whole network, meaning all nodes in the oversized cluster will not be guaranteed a time slot each round, see Figure 2.12.

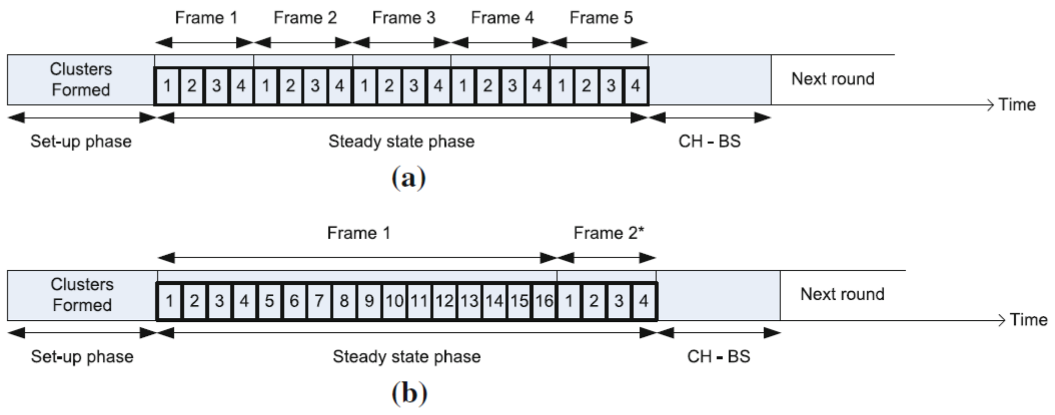


Figure 2.12: Time line for a small (a) and large (b) LEACH-cluster [16].

Therefore, LEACH is only suitable for low data traffic applications. Furthermore, since LEACH utilizes single-hop routing where each node can transmit directly to the cluster head or base station it also falls short in applications where the sensor nodes are deployed in large regions.

2.2.7 Power consumption

Due to the power consumption constraint in most WSNs, it is important to evaluate exactly what consumes power in the system. This section will review what consumes power in a sensor node, and how to minimize the consumption for the MCU.

When minimizing power consumption for nodes in a WSN, the aim is to prolong the life span of each node as much as possible. The life span t_{life} of a node is decided by the battery energy capacity, $E_{battery}$, according to the following relationship:

$$E_{battery} = \int_0^{t_{life}} P_{node}(t)\, dt, \tag{2.14}$$

where $P_{node}(t)$ is the power which variates over the time t. The power P_{node} is the sum of the power drawn by all the components in the node, and is denoted by:

$$P_{node} = \sum_{i=1}^{n} P_i\ . \tag{2.15}$$

where n is the total number of components. Components that consume power in a sensor node like [27, 28, 29] include:

- P_{MCU} : Microcontroller
- P_{flash} : Flash Memory
- P_{radio} : Radio Transceiver
- P_{sensor} : Sensors
- P_{LED} : LEDs

If the system is defined as a proactive one, like most applications in precision agriculture, the node will sleep for long intervals, wake up to sample data and then send/forward to the base station, see Section 2.2.1. The normal procedure for a sensor node will then be:

1. Wake up from sleep state.
2. Turn on sensor.
3. Do sensor measurements.
4. Turn off sensor.
5. Turn on radio.
6. Wait for acknowledgement to send.
7. Send data via the radio.
8. Turn off the radio.
9. Go back to sleep.

If the power of the node is averaged out every active sampling cycle, $P_{active,avg}$, the previously mentioned procedure can be summarized as:

$$E_{cycle} = P_{active,avg} \cdot T_{active}, \tag{2.16}$$

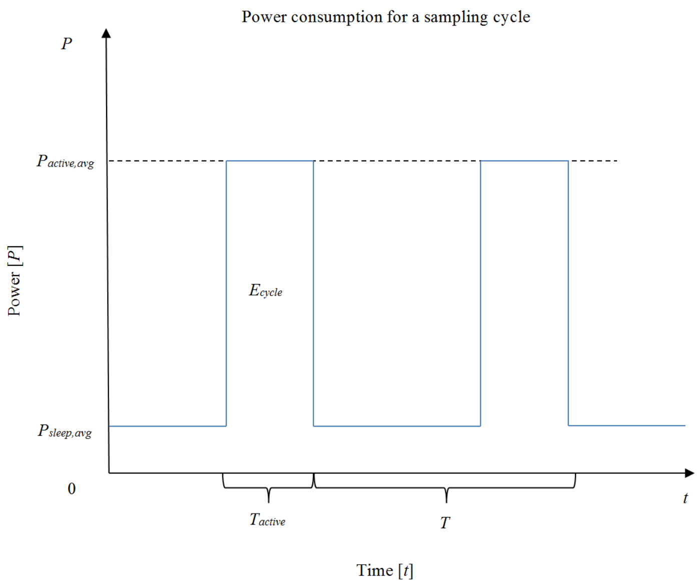


Figure 2.13: Power consumption for a sampling cycle for one sensor node.

see Figure 2.13, where T is the period of the system. As commonly known, the power P in electrical circuits is defined as:

$$P = U \cdot I, \tag{2.17}$$

and as the required voltage level is predefined by the sensor circuit, the goal is to minimize the current consumption of each component i, and the time t_i that each component is active.

3 State of the Art

Unlike the theory chapter this part of the thesis aims to cover what is at the forefront of the different areas of the regarding system design within the agricultural domain aimed at irrigation.

3.1 Smart autonomous irrigation

Smart autonomous irrigation is a fast-growing development area due to the advancements in other scientific fields, like sensor technology and internet availability. A lot of the advancements have been made in the United States of America, where also most of the companies and products reviewed in this section have emerged.

An autonomous irrigation system is defined as a system that irrigates without the user interfering. The 'dumb' autonomous system is referred to as a irrigation clock. It works as the name suggests, irrigating after a periodically set timer, and is the standard system used in the industry. However, this puts demands on the user to make sure the system does not over- or under irrigate the crops. In comparison, a smart irrigation system is defined as a system in which the water distribution, both in timing and amount, is changed dynamically with respect to outer factors. [4]

Terms and concepts

To understand the concept of irrigation and the products on the market today, a few terms and concepts have to be explained:

- A 'smart' irrigation unit is referred to as a controller.
- To convert an existing 'dumb' irrigation unit (ex. an irrigation clock) into a controller, the user can approach the problem in two ways. The controller can either be integrated with the already existing system (Add-On) or it can replace the old system entirely (Stand-Alone).
- All products mentioned in this section are run on 24 VAC, converted from 110-120 VAC.
- All the controllers utilize a MCU to calculate and schedule irrigation.
- Most modern irrigation systems can schedule the watering amount and timing differently in different zones. A zone is the area watered by one or more water distributors, like one or more sprinklers. Different zones may have different properties, like plant type or slope angle, and programming the water distribution differently for each zone may be crucial for efficient irrigation. [4]

There are a few ways to implement said smart system, and two dominating techniques for smart autonomous irrigation on the market today is the weather-based approach and the soil moisture sensor approach. A few products enhances the performance in the weather based calculation by utilizing a soil moisture sensor, and those are mentioned in the end of this section. The different approaches are presented in Section 3.1.1 to 3.1.2.

3.1.1 Irrigation based on weather

By monitoring the weather conditions of the area, a weather-based system can utilize the *ET*-Equation (2.6) in conjunction with the Soil water balance Equation (2.2) to estimate the needed irrigation.

Simply put, the controllers estimate how much water is depleted from the soil and then compensate the water loss with irrigation. The goal is to keep the plants within the thresholds of their soil moisture target, see Section 2.1.1. The more accurate the calculations of *ET* are, the better the applied amount of water mirrors the plants' need. The accuracy of the *ET* equations is improved by monitoring as much of the variables locally, and not relying on standard or remotely calculated values. To adjust the system to every location's unique characteristics, variables like soil properties, plant type, root depth, slope conditions etc. are often defined in the system to get more accurate irrigation calculations. The available monitoring techniques will be presented in the rest of Section 3.1.1.

Historical ET scheduling

As *ET* often has the same value for the same time every year, scheduling irrigation with historical *ET* determined by time of year and zip code (location of the field of interest) is therefore possible. The historical data is stored in the MCU memory. This is implemented as the main source of data in [30] product, and used as a complement together with weather sensors in products [31] and [32]. It can also be a back-up solution when the main source of information fails to be acquired, as is done by the controllers [31] and [33]. The irrigation for this solution changes dynamically, but as the data is predefined the system is not 'smart' in the defined sense mentioned in the beginning of the section.

Weather sensors

As weather is an unpredictable force of nature, there are a lot of different parameters that can be measured to anticipate what the weather will be like. A few of these parameters are relevant to the *ET*-equation, and can be monitored with different sensors. The sensors mostly utilized are different kinds of rain sensors. Most of the systems on the market, like those reviewed in [4], include a rain sensor or rain gauge, or include the possibility to add one to the existing system [4, p. 11] [34].

A well-implemented feature among those who have integrated rain sensors, is that whenever rain starts falling, the current irrigation scheduling is interrupted. The irrigation is then put on hold until the rain stops, as implemented in the controller [35]. This is done to prevent water from being wasted. Some systems, like [36], have integrated air temperature sensors that can shut down irrigation if the temperature drops below 0 °C, to keep the plants from freezing. Other weather sensors worth mentioning are wind, solar and relative humidity sensors, which help increase the accuracy of the *ET* equation. Such sensors are used in [37], [36] and [38]. Some systems, like [39] and [40], actually utilize or can integrate a fully functioning local weather station.

Weather station data

Irrigation can, apart from using historical *ET*-data and locally implementing sensors, be scheduled with data acquired from online weather services, as done by the products [41] and [42]. If this kind of service is implemented, the data can be collected from 9,000 [39] up to 44,000 weather stations [42]. Due to many commercial and residential implementations of autonomous irrigation systems that upload their locally calculated *ET* to the Internet, websites monitoring this *ET* is now available for private and commercial use [43]. This means that more systems can utilize this data, speeding up the implementation of autonomous systems even more.

The same interrupt feature used by rain sensors, to turn off the scheduled irrigation when rain starts falling, is used by weather station data systems, like done in [44].

The use of a locally implemented weather station versus the use of collecting data from online weather forecast services can be discussed. As previously established, the more data that is acquired locally, the more accurate the *ET* equation will become. With that said, if more sensors are implemented, the accuracy will increase. However, if the price is an issue, it is of course better to rely on data from other weather stations. If the system should choose what weather sensor to integrate, the rain sensor is the most popular one, and also the most useful due to the rain interrupting feature and in use to prevent over-irrigation [4].

If the irrigation system collects data from a weather station, the controller needs to have access to internet. Products that have implemented this feature take advantage of the internet access by creating a two-way communication. This means that the user can monitor the system from afar, by using interfaces like a computer or smart phone, as done by [44]. Other features, as implemented by [45] and [39], includes changing the irrigation schedule and update plant types. A few systems, like [37], that does not utilize weather station data have internet access as an add-on feature, as well as radio remote controls.

3.1.2 Irrigation based on sensors

Most of the smart irrigation systems that utilize soil moisture sensors work in the same way. The controller is attached as an Add-On onto the existing timer-based irrigation scheduler, and uses interrupts to change the default timer settings. The sensor is wired to the control box, where a soil moisture target threshold, known as a 'trigger point', has been programmed. This trigger point value can be set by the user, or calculated by the system ([46]) if it is a more sophisticated one. If the soil moisture is less than the pre-programmed threshold value, the controller urges the system to irrigate right away. This is known as a reactive system and can be seen as an alarm-mechanism, preventing the soil from ever getting too dry. At all other times, the standard timer will conduct the irrigation, as products [47], [37] and [48] have done. As the sensors are wired, often along the same wires that control the valves, it is impractical to use more than a few sensors [49]. This means one soil moisture sensor is used to control more than one zone, even though the zones have different water needs and ET-constant. This can be a more or less serious issue depending on the plants being grown.

The product supplied by [40] can integrate their soil moisture sensor with the ET-calculations supplied by weather data, to create a feedback system. This addresses the issue with not knowing the initial moisture levels when irrigating, and during the process validates the accuracy of the ET values.

3.2 WSN in precision agriculture

All of the mentioned available solutions above have one thing in common, assumptions of heterogeneity as none of them provide the dense monitoring needed in order to adapt the irrigation to the micro-climate fluctuations within the area. Dense monitoring here refers to the possibility, provided by wireless sensors, to monitor crop close enough to register fluctuations in the micro-climate, the term together with used metrics are further explained in Section 6.1.1.

However, contrary to these existing approaches, precision agriculture aims at eradicating these assumptions of heterogeneity. Precision agriculture in this context refers to the four-stage process using techniques to observe spatial variability [50]:

- **Geolocation**: The land being cultivated is delineated in order to be able to overlay information gathered from soil analysis and information on previous crops and soil resistivity.
- **Characterizing variability**: Fluctuations and variations in the field can depend on a number of factors, such as climatic conditions (hail, drought, rain, etc.), soils (texture, depth, nitrogen levels), weeds and disease. These are monitored either by permanent indicators (soil indicators), which provide information on the environmental constants, or by point indicators (weather station, temperature/light sensors, soil moisture sensors), which

allows tracking of a crop's status, i.e. possible disease outbreaks, water stress, nitrogen stress, frost damage and so on. Permanent indicators combined with point indicators make it possible to precisely map agro-pedological conditions.

- **Decision-making**: How to act on the gathered data.
  - Predictive approach: Decisions are based on analysis of static (permanent) indicators during the crop cycle.
  - Control approach: Decisions are based on analysis of static (permanent) indicators which are updated during the crop cycle by sampling, remote sensing or satellite sensing (for example).
- **Adapt practices**: Adjust irrigation, harvest schedule and seed density during seed time according to the geological variations of the crop.

It is in the context of precision agriculture that WSNs becomes interesting. As mentioned in Section 1.1 WSNs have just recently been gaining momentum in the field of agriculture. Between 2004 and 2010 several interesting studies, such as [7, 5, 6, 9], were carried out with the aim of establishing whether the dense monitoring provided by the WSN technology would prove to be agricultural significant. In other words, how much of an issue are the now used assumptions of heterogeneity and are there other, yet unknown, advantages of such dense monitoring?

The answer turned out to be yes as the research conducted proved that the monitored fluctuations of the micro-climate (provided by the dense monitoring) indeed is of importance when tracking everything from irrigation needs and fruit maturity to heat accumulation and possible pest outbreaks [7, 5, 6].

Although almost all existing irrigation systems today still neglect this fact, there are in fact a few crop-monitoring solutions on the market today that monitor the micro-climate. This implementation is referred to as Wireless Crop Monitoring.

3.2.1 Wireless crop monitoring

Apart from the smart irrigation systems, there are a few wireless crop monitoring systems on the market. They utilize wireless communication and multiple sensors to monitor all kinds of relevant environmental data. The data is not used to correct irrigation, but to analyse the micro-climate to enable the user to do improvements as deemed necessary. The implementations have some common traits worth mentioning:

- **Energy Source**: The wireless units on the market are all, as the name suggest, disconnected from the power grid. [51] utilizes both 3 AA batteries and solar panels as energy sources, while [52] uses 2 AA alkaline batteries.
- **Communication Protocol**: [51] uses a low-power mesh network over a 802.15.4 protocol to communicate, while [52] and [53] uses direct transmission. [53] have repeaters that can be implemented that strengthens the signal from the field unit to the base station.
- **Expected life span**: [53] have a life expectancy of up to 6 years on the built in long-life internal battery source, while [52] have 6 months. Without the solar panels [51] have a life expectancy of 3 months, but if the panels are utilized the unit is estimated to survive more than 5 years.
- **Reach**: The product [52] have a reach up to 300 m, whereas [53] and [51] have a range up to 3 km.

- **Sampling Interval**: The sampling interval ranges (as default values) from 1 [52] to 15 [51] minutes.

The usage of the mentioned units differs. The [52] wireless sensing units are paired with a monitoring unit that can interact with up to 16 sensing units. 8 of these units can be set to trigger an alarm. [51] uses a "Base Radio" to be connected to a Gateway device run on Debian Linux, to provide an interface to view data, run reports and set up alarms if any of the collected data is out of the ordinary. [53] uses a base station receiver that is to be plugged into a PC. Software provided by [53] is intended to help the user to analyse the crops and schedule the irrigation better, but not as a first-hand controller. These three systems are not intended to be utilized directly with a smart irrigation scheduler, but more as a tool to analyse the crops and then manually correct the irrigation if needed.

All the products can utilize sensors that monitor the environment. [51] have 4 sensor ports where the 4 sensors provided by the manufacturer can be integrated. [52] utilizes air temperature and relative humidity sensors. [53] can integrate everything from soil moisture, pressure, air and soil temperature sensors to be used together with a fully working weather station.

This leads to the conclusion that there exists WSN solutions for precision agriculture, but they are not well integrated with the actual irrigation.

3.3 System design

As proven in Section 3.1, detailing the market for irrigation systems and wireless crop monitoring, the different design aims vary greatly from product to product and very few have made the energy efficiency of the system a priority. Certain systems even utilise wired sensors like [49, 47, 37], and others AA batteries with varying lifetime [51, 52].

The reason WSN versions of irrigation systems haven't made power consumption a priority (yet) is largely due to the fact that WSNs just recently started gaining momentum in the field of agriculture and that together with cheaper hardware and emerging non-proprietary software changed the conditions.

As a result, very few out of the conducted studies ([7, 5, 6, 9, 54, 55]) (performed between 2004-2010) put much, if any, effort into the power management aspect of the network design. Furthermore, it's not just a matter of power optimization, there's a permanent trade-off between power management and robustness that for every given WSN implementation needs to be addressed.

This section will therefore present the existing approaches and solutions to the power management and robustness design choices.

3.3.1 Deployment

As mentioned in the Theory chapter, node deployment can either be random or deterministic. Since farm lands are inherently easily accessible (because they are harvested), and not seldom also quite uniform in size and dimension, deterministic deployment is most frequently used. Random deployment serves no purpose in an agricultural context where coverage is the main goal and data redundancy something to be avoided. This is evident since all the studies in [7, 5, 6, 9, 55] have utilized deterministic deployment of nodes.

In [7] the aim was to position the nodes in a very dense grid pattern in order to investigate how dense the monitoring needed to be for the data to be agricultural significant. They reached the conclusion that depending on what parameters are being monitored the density of the network may vary. For temperature profiles and fruit maturity for example, nodes 25 meters apart would suffice, whereas nodes needed to be closer (15 m) to monitor possible pest outbreaks or frost damage. Thus, the prevailing node deployment has been and probably will continue to be deterministic deployment because of the inherent characteristics of agriculture.

The density of the monitoring however, remains tightly linked to the implementation and isn't an absolute number that can be applied in all settings. As is pointed out in [7, 5, 6, 9] the successful implementation of an autonomous WSN irrigation system postulates the help of biologists, ethnographic research, farmers and agricultural specialists in order to design the system correctly.

3.3.2 Routing power consumption

When designing a robust and power smart irrigation network, routing is of utmost importance. This since the possibility of hardware power handling today is mostly already taken care of by the operating system automatically (see Section 4.3 Node specifications in Method). What remains then is how to organize the network itself and the data forwarding.

When comparing the performance of two or more routing protocols different approaches can be useful. To get an indication of how well suited certain protocols are for an already known testbed, the First Order Radio model can be of great use [56]. It is an analytical model frequently used in WSN research to estimate the power consumption of a routing protocol and is usually the first step in the evaluation of a new protocol. The results are then often compared to simulation results (COOJA/TOSSIM) and possibly even actual deployment data, with very good results. [1, 57, 58, 59]

According to the hardware independent First Order Radio model the energy consumed by the electronics needed to operate the transceiver circuit is $E_{elec} = 50\frac{nJ}{bit}$ and the energy needed to run the transmitter amplifier is $\varepsilon_{amp} = 100\frac{pJ}{bit}/m^2$. This results in the following equations for receiving and transmitting a k bit message over a distance d.

$$E_{Tx}(k,d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2 \tag{3.1}$$

$$E_{Rx}(k) = E_{elec} \cdot k \tag{3.2}$$

As shown in the equations, both transmitting and receiving a message is a high overhead procedure, which is why both should be kept to a minimum. However, it's more complicated than that. In the Direct Transmission protocol receiving overhead is minimized since all nodes transmit to the sink, but at the same time the transmission costs are huge due to the large distances packets have to travel. This means that for a flat protocol the worst case scenario of how far a node must transmit is inherently dependent on the scale of the system and the node's distance from the sink node. In other words such a protocol doesn't scale well at all.

In multi-hop protocols however (which minimize travel distance), transmission are kept very short but then the number of receiving actions increase dramatically. In other words, a multi-hop protocol might not necessarily improve the battery lifetime since an ill-suited algorithm could cause data to travel via sub-optimal routes to the sink and thereby require too many relaying operations.

This leads to the conclusion that routing protocols must always be well tailored to their implementations. However, with the help of Equation (3.1) and (3.2) the situation when direct transmission consumes the same amount as multi-hop can be found, see Section 3.3.2 below.

Direct Transmission vs Multi-hop

Consider Equation (3.1) and (3.2), the difference between DT and multi-hop is that rather than just one (high-energy) transmit of the data (DT), each data message must go through n low energy transmits and n receives (multi-hop). [57] [60]:

And depending on the cost for those operations the total energy expended in the system might be greater using multi-hop than direct transmission to the base station. This phenomenon is illustrated in Figure 3.1.

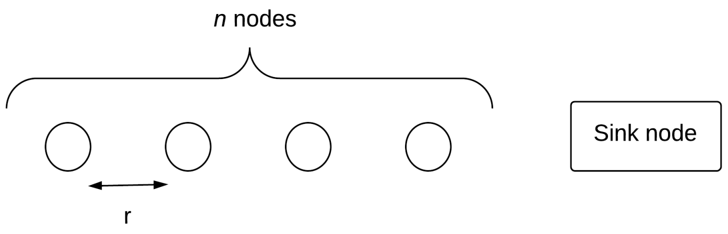


Figure 3.1: Four nodes, r distance apart.

As seen in Figure 3.1 the distance d can be rewritten as $d = n \cdot r$, since all nodes in a deterministic deployment are stationary leading to the fact that the distance from sensor node to sink node is fixed. Thus, Equation (3.1) can be rewritten as:

$$\begin{aligned} E_{Tx}(k,d) &= E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2 && (3.3)\\ &= E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot (n \cdot r)^2 && (3.4)\\ &= k(E_{elec} + \varepsilon_{amp} \cdot n^2 \cdot r^2) && (3.5) \end{aligned}$$

In multi-hop routing, each node sends a message to the closest node on the way to the sink node. Thus the node located a distance $n \cdot r$ from the sink node would require n transmits a distance r and $n-1$ receives. This leads to:

$$\begin{aligned} E_{multi-hop} &= n\ E_{Tx}(k, d=r) + (n-1)\ E_{Rx}(k) && (3.6)\\ &= n\ (E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot r^2) + (n-1)\ (E_{elec} \cdot k) && (3.7)\\ &= k\ (\ (2n-1)E_{elec} + \varepsilon_{amp} n r^2\ ) && (3.8) \end{aligned}$$

Thence, direct transmission requires less energy than multi-hop if:

$$\begin{aligned} E_{direct} &< E_{multi-hop} && (3.9)\\ E_{elec} + \varepsilon_{amp} n^2 r^2 &< (2n-1)E_{elec} + \varepsilon_{amp} n r^2 && (3.10)\\ \frac{E_{elec}}{\varepsilon_{amp}} &< \frac{nr^2}{2} && (3.11) \end{aligned}$$

For most agricultural implementations Equation (3.11) will not hold true because of the large distances the WSN has to cover, but for smaller implementations in botanical gardens or green houses it's worth considering that a direct transmission might fulfil the power consumption goals better than a multi-hop scheme.

3.3.3 Robustness

Robustness is another issue which must be overcome when dealing with WSNs in precision agriculture. There are several existing definitions of when the network is considered dead, of which the two prevailing are "first node dies" and "XX% of the nodes have died" (usually 25%). For agricultural purposes both can be used, but depending on the node deployment and network design the system might become unusable as soon as the first node dies or it might be able to sustain the needed functionality for much longer. This is where the question of robustness comes into play, how much failing links and nodes should an irrigation system be able to handle?

As mentioned in the Theory chapter 2, data redundancy is a real and very common issue in WSNs (see Figure 3.2). This would implicate that, since most nodes have some overlap in reported sensor data, the network as a whole would not suffer greatly if some nodes depleted their battery resources earlier than others. However, if this is to be a design choice, the network and routing scheme must mirror this.

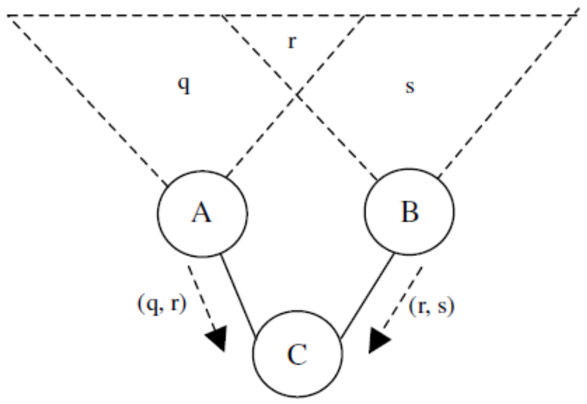


Figure 3.2: The data redundancy issue. Node A and B overlap and will both be reporting sensor data regarding area r to the sink node C. [18]

For example, if the routing scheme is direct transmission, dying nodes would mean leaving certain areas uncovered, but that would hopefully, for a short time, be remedied by other nearby nodes reporting overlapping data. This set-up might work for a while but will inevitably lead to necessary battery changes to restore the functionality of the network.

If the routing scheme instead consisted of a hierarchical tree protocol, the issue of nodes depleting their batteries becomes something else entirely. A node in the middle of the tree acts as a forwarder for the leaf nodes below it, meaning that if that node dies no data will be forwarded from its leaf nodes, leaving a much larger area unmonitored. The existing studies have chosen different approaches to the robustness issue.

In [7] 65 nodes were deterministically deployed in a multi-hop network which utilized static routing tables and no neighbour discovery. The reason for this was the assumption that, since the nodes would not be mobile, neighbour discovery wouldn't be necessary and by extension neither dynamic routing tables. This might seem like a sound assumption at first but, as the authors found out, the gain in lowered power consumption was 'lost' in the resulting low packet receiving rates and robustness and the many lost links and missing data. Nodes would sporadically leave and rejoin the network causing large areas to intermittently be unmonitored (no possibility of finding new routes with static tables). Furthermore, they found that the backbone nodes (functioning somewhat like static cluster heads) only lasted six weeks in spite of the oversized 42 Amp hour batteries.

The authors of [5] deployed a self-organizing ad-hoc type network of 18 nodes but realized, after having conducted in-depth ethnographic research, that this might not be the optimal choice. As future work they suggested an architecture which would use *data mules*, meaning that the sensor nodes would implement neighbour discovery and simply send the accumulated sensor data to a sink node attached to farming equipment or workers as they traverse the area. This way all nodes would save energy by transmitting seldom and only over short distances. However, this approach might not at all help the power consumption since this would force all nodes to idle listen for long periods of time. Furthermore scarce monitoring might result in insufficient data for precision agriculture.

The tree topology is advocated only by the authors of [9] as a part of the MINT protocol. However, those nodes only stayed active for 3 weeks on their original batteries.

The only study that implemented a self-healing robust system was [6]. The authors deterministically deployed 64 TelosB nodes covering an area of 0.5 hectare, which utilized a self-healing multi-hop architecture. In comparison to the other studies performed very few issues arose due to system robustness or power consumption with this approach. The authors conclude that the average overhead for the communication is quite low compared to achieved robustness: 56 bytes per transmission round. This would indicate that the proposed savings in power, due to the static routing tables in [7], are negligible in comparison to the gains in robustness.

As mentioned in the Theory chapter cluster based routing schemes are considered to be the best in terms of robustness, scalability and power management but how well they perform is tightly linked to how the cluster heads are chosen and their clusters are formed. At the forefront of this are the authors of [59] who utilize multi-criterion optimization (MCOP) or multi-objective decision making, which is an engineering design method that deals with problems that have several conflicting and possibly non-commensurable criteria which should be simultaneously optimized. Exactly how the MCOP is implemented and its benefits are explained in the following sections.

3.3.4 Cluster based routing schemes

As mentioned in the chapter 2 (Theory), there are a number of available routing schemes. Out of these, the cluster based approach has proven to be the most power efficient, robust and scalable [59] and is classified by the following criteria:

- **Clustering method**: distributed or centralized. A distributed approach means that each node makes its own decisions and calculations regarding whether to become cluster head (CH) and which cluster to belong to, as opposed to letting the central main frame make all of those decisions.
- **Network architecture:** single or multi-hop. Single-hop architectures make no use of forwarding or relaying of packets between nodes, whereas multi-hop do.
- **Clustering objective:** energy efficiency or coverage. Is the aim to lower power usage or to provide coverage? Each is chosen at the expense of the other.
- **Cluster head selection method:** random or deterministic. Random cluster head selection (as in LEACH) means that the choices and parameters are local to each node. In other words, the effect on the system as a whole isn't weighted in [61].

As this thesis focuses on a WSN meant for implementation within the area of irrigation, the following characteristics are suitable:

- **Clustering method:** distributed.
- **Network architecture:** multi-hop.
- **Clustering objective:** energy efficiency.
- **Cluster head selection method:** deterministic.

In the subsequent sections the state of the art approach for cluster head selection and cluster formation, called MOECS (Multi-Criterion Energy Consumption Optimization), will be presented and discussed.

3.3.5 Multi-criterion energy consumption optimization

Each transmission round in a clustered WSN consists of two phases: cluster formation and data transmission. The former can be divided into two sub-categories: **cluster head selection** and **cluster formation**, which are pivotal for balancing the energy dissipation of the network. In the sections below, both will be discussed.

Cluster head selection

To minimize the energy consumption of a clustered WSN, there needs to be a certain number of cluster heads (CHs) present (dependent on the total amount of nodes) and they need to be well distributed through out the system. This in order to guarantee good coverage and/or load distribution.

Once this optimal number of CHs has been decided, the selection process begins which can be either random or deterministic. Random cluster head selection means that the role of cluster head is randomly rotated among the nodes. Since this approach doesn't take any node or system parameters into account it results in a less than optimal result where the distribution of CH is uneven and the energy dissipation of the network non-uniform [59, p. 205].

Deterministic selection however, means the opposite. Here a node becomes cluster head based on a pre-determined parameter, such as residual energy, number of one-hop neighbours or distance to base station etc. Thanks to this pre-determined parameter the network lifetime is prolonged since the load is more evenly distributed within the cluster.

However, the future of solving these cluster head and formation issues are through multi-criterion optimization (MCOP) or multi-objective decision making, which is an engineering design method that deals with problems that have several conflicting and possibly non-commensurable criteria which should be simultaneously optimized. Hence, a new approach has been suggested by [59], called MOECS (Multi-Criterion Energy Consumption Optimization).

In MOECS, the election process for CHs looks like this:

- Each node randomly chooses a number between 0 and 1 and then calculates its probability of becoming CH according to the following equation (referred to as a probability function):

$$T(n) = \frac{p}{1 - p(r \cdot mod\frac{1}{p})} \tag{3.12}$$

  where p is the optimal number of cluster heads (estimated at 5% of the total number of nodes), r is the current transmission round and $n \in G$, where G is the set of nodes which have not been cluster heads in the last $\frac{1}{p}$ rounds. [18]
- The nodes which are elected `CANDIDATES` (number lower than threshold) broadcast a `COMPETE_HEAD_MSG` within the radius $R_{compete}$.
- If the node discovers another `CANDIDATE` within $R_{compete}$ with higher residual energy the node will drop out of the competition without receiving any sub-sequential `COMPETE_HEAD_MSG`s.
- If the node doesn't receive any `COMPETE_HEAD_MSG` from nodes with higher residual energy, it's elected `HEAD`.

The number of nodes that can become `HEAD` is managed by adjusting the value of $R_{compete}$, since a node only competes with other nodes within the $R_{compete}$ there cannot be two CH within the same $R_{compete}$, which in turn guarantees an even and optimal distribution of CHs [58, p. 538]. $R_{compete}$ is calculated with the following equation:

$$R_{compete} = \sqrt{\frac{M^2}{\pi K_{opt}}} \tag{3.13}$$

in which M^2 is the deployment area and K_{opt} the optimal number of cluster heads for this particular set-up. This optimal number of cluster heads, K_{opt}, is best calculated, according to the authors in [59], who base their choice of K_{opt} on the works of [62], with the following equation:

$$K_{opt} = \sqrt{\frac{\varepsilon_{fs}}{\pi(\varepsilon_{mp} d^4 - E_{elec})}} M\sqrt{n} \tag{3.14}$$

where n is the number of nodes, M^2 is the deployment area, d^4 is the fourth power distance to the base station, ε_{fs} the energy consumed in the amplifier transmitting at a distance shorter than $d_{crossover}$, ε_{mp} the energy consumed in the amplifier transmitting at a distance greater than $d_{crossover}$ and E_{elec} the energy needed to operate the transmission circuit.

The transmission in a WSN are assumed to be kept at a fixed power level, meaning that should a node have to transmit further than the originally intended distance, more energy will be used, see equation below.

$$E_{Tx} = \begin{cases} l \cdot E_{elec} + l \cdot \varepsilon_{fs} \cdot d^2 & \text{for } 0 \leq d \leq d_{crossover} \\ l \cdot E_{elec} + l \cdot \varepsilon_{mp} \cdot d^4 & \text{for } d \geq d_{crossover} \end{cases}$$

Cluster formation

Historically, in cluster formation algorithms, the decision regarding which cluster to join has been based solely on minimal communication cost. This approach has been widely exploited by, for example, the authors in [63] who base the choice of which CH to join on signal strength and the authors in [58] who use a weighted cost function. However, with the help of MCOP, which is inspired by preference function modelling and has been successfully used to find an optimal path based on multiple user constraints, an even better result has been achieved. The basic idea is to use a preference function which accepts a value from user criterion x and returns a value s(x) scaled between 1 and -1 (1 represents the best and -1 the worst value respectively). A decision matrix is built and used to find the optimal choice for a given criterion. The preference vector contains the scaled weighted values for each of the parameters involved in the decision process. The weight matrix is obtained by multiplying the decision matrix with the preference vector to find the weight for each of the available choices. The maximum weight in the weight vector indicates the best choice, see the flow chart in Figure 3.4 which describes the steps of the cluster formation algorithm. [59]

This leads to better choices when forming clusters, which in turn results in better load balancing, a more even energy dissipation of the network and thereby longer network lifetime, see simulation results in Figure 3.3.

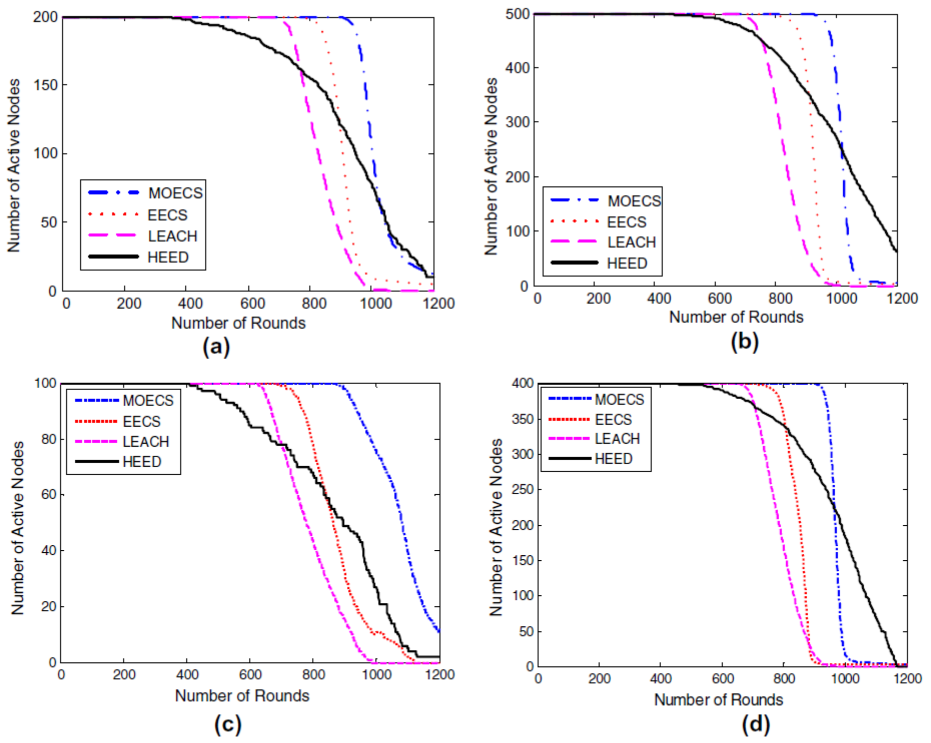


Figure 3.3: Network life in rounds for: (a) random topology 200 nodes, (b) random topology 500 nodes, (c) grid topology 100 nodes and (d) grid topology 400 nodes. [59]

As can be seen in Figure 3.3 a) and b) demonstrate the results for randomly deployed nodes on an area of 100 x 100 meters and c) and d) the results from a grid topology (more interesting from an agricultural point of view).

In a) and b) the first node death occurs after 920 and 980 rounds respectively and under this criterion MOECS extends the network lifetime with approximately 10 % compared to EECS, 25% compared to LEACH and 200% compared to HEED. In c) and d) the results are similar.

But if the first node death is substituted for 20% and 50% dead nodes, the results for HEED are actually comparable to MOECS under large node densities.

In other words, MOECS is the now reigning cluster based protocol showing the best performance. However, worth noticing is that the research on MOECS was first published in 2008, i.e. after many of the mentioned studies on WSN and irrigation had been made. The only study to be released afterwards, in 2010, is [6] in which the use of a much more primitive cluster based algorithm is explored.

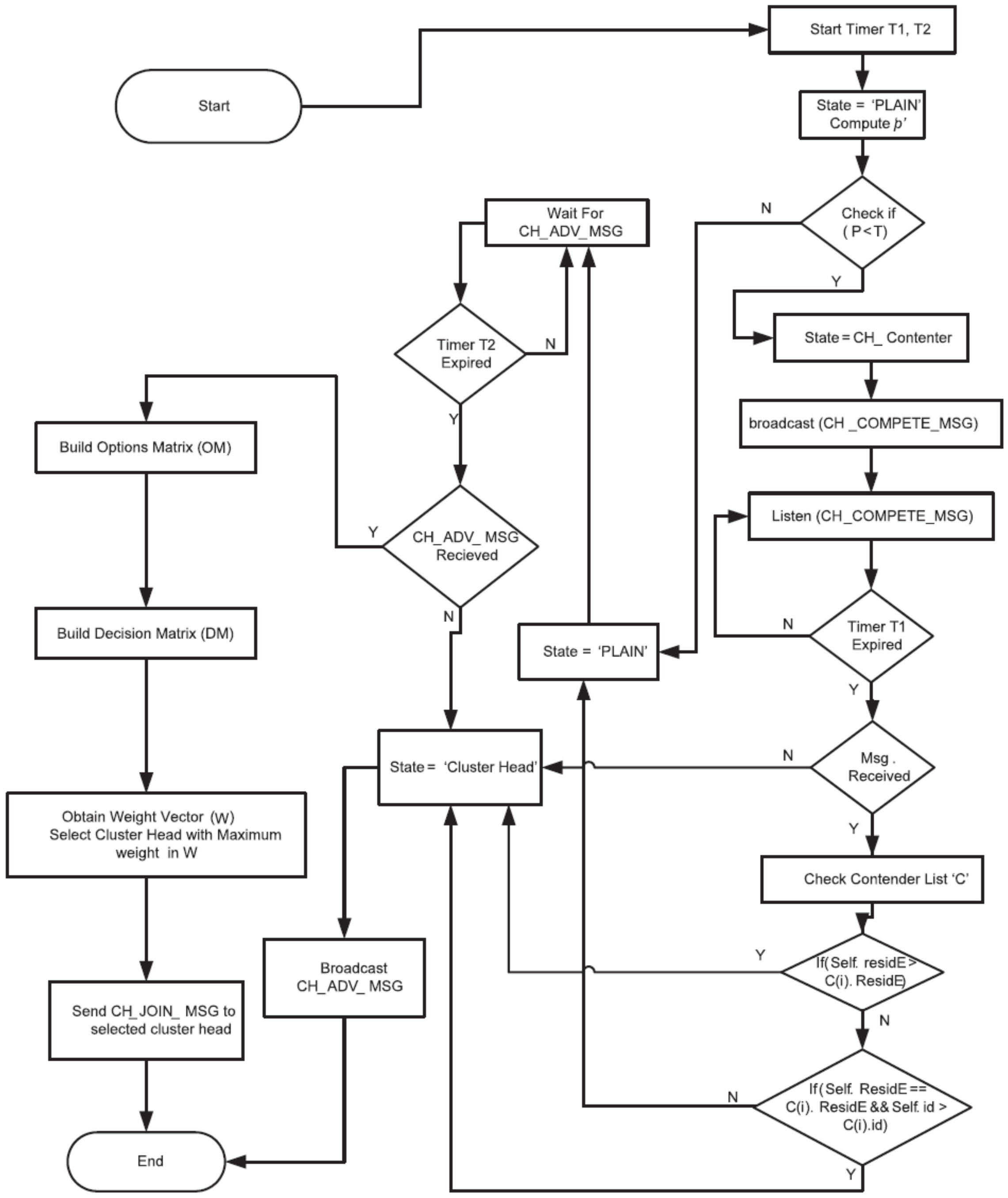

Start
Start Timer T1, T2
State = 'PLAIN' Compute p'
Check if (P<T)
N
Y
State = CH_ Contenter
broadcast (CH _COMPETE_MSG)
Listen (CH_COMPETE_MSG)
Timer T1 Expired
N
Y
Msg . Received
N
Y
Check Contender List 'C'
If(Self. residE > C(i). ResidE)
Y
N
If(Self. ResidE == C(i). ResidE && Self. id > C(i).id)
N
Y
Wait For CH_ADV_MSG
Timer T2 Expired
N
Y
CH_ADV_ MSG Recieved
Y
N
State = 'PLAIN'
State = 'Cluster Head'
Broadcast CH_ADV_ MSG
Build Options Matrix (OM)
Build Decision Matrix (DM)
Obtain Weight Vector (W) Select Cluster Head with Maximum weight in W
Send CH_JOIN_ MSG to selected cluster head
End

Figure 3.4: The cluster formation algorithm in MOECS [59].

3.3.6 Power mode handling

Apart from the power consumption of the network, the power consumption for the MCU is important to consider. The power consumption for a MCU can be divided into two categories, the power consumed while being *a)* Active, *b)* Idle. Easily put, active is when the MCU have tasks to execute, and idle is when the MCU waits for new tasks. If, for example, the current consumption of the MSP430, a commonly used MCU for wireless sensor nodes [64], is studied, see Table I, the difference is easily observed. The technique of choosing the correct power state for an MCU while being idle is called Power Mode Handling.

Table I: Nominal current consumption by a TI MSP430f2617 microcontroller. [27]

Power State	**Current**
Active Mode at 16MHz	< 10mA
Active Mode at 1MHz	0.5mA
Standby Mode	0.5μA
OFF Mode	0.1μA

To save energy when the node is not performing any tasks, the MCU have to make sure the processor uses the correct power mode when being idle. For example, as can be seen in Table II, the MSP430 uses less clock and oscillator modules if the power mode is lowered. As the authors of [65] and [66] explains, an algorithm which can determine the optimal power mode for a threshold time t is therefore needed in systems that want to decrease the total power consumption.

Table II: Clocks on/off in different Low Power Modes for MSP430f2617 [67]

Mode	**Active**	**LPM0**	**LPM1**	**LPM2**	**LPM3**	**LPM4**
CPU	On	Off	Off	Off	Off	Off
MCLK	On	On	Off	Off	Off	Off
SMCLK	On	On	On	Off	Off	Off
DCO	On	On	On	On	Off	Off
ALCK	On	On	On	On	On	Off
Crystal Oscillator	On	On	On	On	On	On

The first energy cost to take in account when deciding if a device should change its power mode, is the cost of power when transitioning. To justify a transition on the MSP430f2617 microcontroller (see Table I) between, for example, the two states *active* and *standby*, the energy saved in the *standby* state should exceed the power-up cost to the *active* state. The energy cost when transitioning the other way around, from *active* to *standby* is in comparison often much lower, and will therefore be neglected in the following equations. Let $t_{standby}$ denote the time the device stays in *standby* state, and $P_{standby}$ be the power consumption in *standby.* The transition time between *standby* and *active* is denoted as $t_{s,a}$, and the power consumed is defined as $P_{s,a}$. Lastly, the power that the *active* state consumes is denoted as P_{active}. Hence, to justify a transition, as [68] explains, the following equation should be fulfilled:

$$P_{standby} \cdot t_{standby} + P_{s,a} \cdot t_{s,a} \leq P_{active} \cdot (t_{standby} + t_{s,a}). \tag{3.15}$$

The time spent in *standby*, $t_{standby}$, is justified if

$$t_{standby} \geq max\left(0, \frac{(P_{active} - P_{s,a}) \cdot t_{s,a}}{P_{standby} - P_{active}}\right) \tag{3.16}$$

The active and standby state can be generalized as a transition between any state i (any higher operating mode) and j (any lower operating mode),

$$t_j \geq max\left(0, \frac{(P_i - P_{j,i}) \cdot t_{j,i}}{P_j - P_i}\right). \tag{3.17}$$

If the transition costs is the same moving from higher to lower as the opposite, the energy saved can be expressed as

$$E_{saved,j} = P_i \cdot (t_j + t_{i,j} + t_{j,i}) - \left(\frac{P_i + P_j}{2}\right)(t_{i,j} + t_{j,i}) - (P_i - P_j) \cdot t_j. \tag{3.18}$$

This means that the power can be decreased by increasing the gap between P_i and P_j, increasing the time t_j spent in state j, or decreasing the transition times.

The authors of [69] argued that an important aspect when scheduling which power mode the processor should enter is to evaluate when or if it should enter the lowest sleep state. This state often has all excess functions off, like the sensor, transceiver and ADC circuits. This means that the only way to wake the node up is to have a scheduled internal interrupt. If the lowest sleep state is used, the program needs to know when the next event is happening, with two approaches to take in consideration. The node can wake up more a bit more often than it should, and risk unnecessary idle time, or wake up less often and risk missing events. The choice is of course based on the system design.

Active mode

Apart from optimizing the power consumption when the node is idle, the power consumption when the node is active can be considered. The relationship between power P and speed s of a processor is often denoted as

$$P(s) = s^{\alpha} \tag{3.19}$$

where $\alpha > 1$ and constant. Equation (3.19) is based on the well-known cube-root rule, which specifies that all in CMOS-based processors, the power is proportional or equivalent to s^3. This phenomena can be observed in Table I. The preferred implementation is therefore to run the CPU at the lowest possible speed setting whenever possible. A speed-scaling problem arises if the deadlines of the task being executed are strict, and can be solved with a technique called *Dynamic Frequency Scaling*, or *DFS* [70].

3.4 The Internet of Things

Beyond the deployment, topology and routing scheme choices listed in the previous sections lies another big decision, whether to construct a so called online irrigation system, meaning whether to have the nodes talk IP or not. The implications of a transition towards an online system will be presented in this section.

3.4.1 The history of Internet of Things

The ability to connect smart embedded objects to the Internet is what is normally referred to as the Internet of Things. However, this transition from "offline" sensor networks to Internet connected networks introduces a number of challenges, all related to successfully porting the use of Internet technologies onto small, low cost, constrained units with limited power, memory and processing power. Furthermore, these embedded devices and their networks display very different characteristics than their big brothers operating in today's Internet: their traffic pattern is different, they suffer from high packet loss, low throughput and frequent topology changes and utilize small useful payload sizes. [71]

There have been several attempts at creating an extension of the Internet to constrained devices in the past few years. But all of them, up until recently, have resulted in proprietary protocols making the interoperability of these vendor-specific Internet-enabled devices impossible, since the connectivity in these networks is achieved through vendor-specific gateways or proxies. Furthermore, with these proprietary protocols the user can only communicate with the nodes through a gateway or proxy that acts as a translator. This solution offers little to no flexibility as the user can only query the sensors according to the API provided by the gateway. On top of that, the use of proprietary protocols means gateways and sensors need to be of the same brand in order to function together. [71]

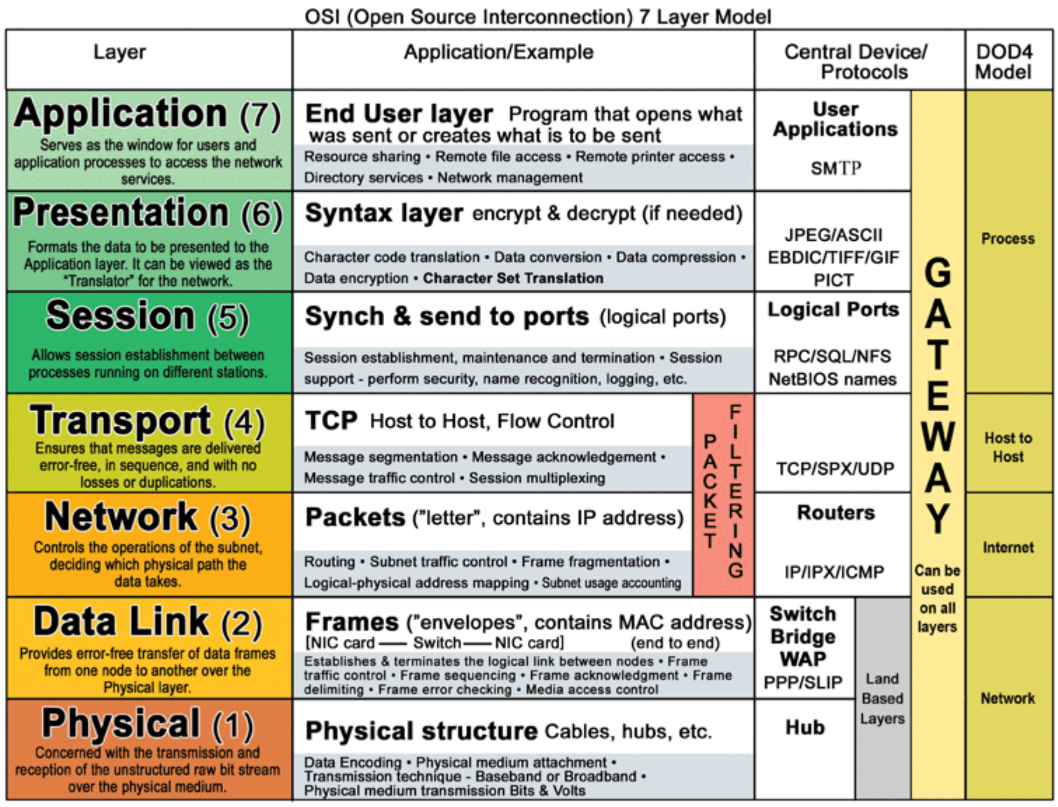
These limitations combined with the curiosity and newly discovered potential of an Internet of Things led to the IETF (Internet Engineering Task Force) initiative [71] to form the 6LoWPAN (*IPv6 over Low Power WPAN*), ROLL (*Routing Over Low Power and Lossy Networks*) and CoRE (*Constrained Restful environments*) working groups, all with the aim of producing a non-proprietary solution, interoperable with the most widely used protocols of the Internet, IP, the Internet Protocol.

The 6LoWPAN group tackles the transmission of IPv6 packets over IEEE 802.15.4 networks, the ROLL group develops routing solutions for LLNs (Low Power and Lossy Networks), of which IEEE 802.15.4 networks are a part, and the CoRE group provides a framework for resource-oriented applications intended to run on constrained IP networks. Together, these protocols, frameworks and solutions allow small constrained networks to run the Internet Protocol in a standardized way. [71]

3.4.2 IEEE 802.15.4 networks

In the subsequent sections, the IEEE 802.15.4 standard, a well known WSN standard, and its layers will be presented.

In order to facilitate the explanation of these concepts, the OSI model, see Figure 3.5, will be presented first to help with an overview of where in the communication model the different standards and protocols operate.


OSI (Open Source Interconnection) 7 Layer Model

Layer	Application/Example		Central Device/ Protocols			DOD4 Model
Application (7) Serves as the window for users and application processes to access the network services.	**End User layer** Program that opens what was sent or creates what is to be sent Resource sharing • Remote file access • Remote printer access • Directory services • Network management		**User Applications** SMTP		**GATEWAY** Can be used on all layers	Process
Presentation (6) Formats the data to be presented to the Application layer. It can be viewed as the "Translator" for the network.	**Syntax layer** encrypt & decrypt (if needed) Character code translation • Data conversion • Data compression • Data encryption • **Character Set Translation**		JPEG/ASCII EBDIC/TIFF/GIF PICT			
Session (5) Allows session establishment between processes running on different stations.	**Synch & send to ports** (logical ports) Session establishment, maintenance and termination • Session support - perform security, name recognition, logging, etc.		**Logical Ports** RPC/SQL/NFS NetBIOS names			
Transport (4) Ensures that messages are delivered error-free, in sequence, and with no losses or duplications.	**TCP** Host to Host, Flow Control Message segmentation • Message acknowledgement • Message traffic control • Session multiplexing	PACKET FILTERING	TCP/SPX/UDP			Host to Host
Network (3) Controls the operations of the subnet, deciding which physical path the data takes.	**Packets** ("letter", contains IP address) Routing • Subnet traffic control • Frame fragmentation • Logical-physical address mapping • Subnet usage accounting		**Routers** IP/IPX/ICMP			Internet
Data Link (2) Provides error-free transfer of data frames from one node to another over the Physical layer.	**Frames** ("envelopes", contains MAC address) [NIC card —— Switch —— NIC card] (end to end) Establishes & terminates the logical link between nodes • Frame traffic control • Frame sequencing • Frame acknowledgment • Frame delimiting • Frame error checking • Media access control		**Switch** **Bridge** **WAP** PPP/SLIP	Land Based Layers		Network
Physical (1) Concerned with the transmission and reception of the unstructured raw bit stream over the physical medium.	**Physical structure** Cables, hubs, etc. Data Encoding • Physical medium attachment • Transmission technique - Baseband or Broadband • Physical medium transmission Bits & Volts		**Hub**			

Figure 3.5: The 7 layer OSI model. [72]

OSI model

The OSI model is a conceptual model which standardizes the internal functions of a communication system by partitioning it into abstraction layers. There are a total of 7 layers and each layer serves the layer above it and is served by the layer below it. When discussing routing, packet transmission and networking in WSNs, it facilitates the understanding of such concepts if the OSI model is kept in mind.

As Figure 3.5 clearly illustrates sensor networks are made up of hardware and above that communication systems which define standards for how the communication is to be carried out, all the way from the application layer down to how the radio is to transmit the package. One of these standards, often used for wireless sensor networks, is the IEEE 802.15.4 standard (present in the Physical and Data Link layer).

The standard specifies the physical layer (PHY) and media access control (MAC) for low-data-rate, low-power and short-range radio frequency transmissions for wireless personal area networks (PANs). It is, for example, the basis for the ZigBee technology. The standard is maintained by the IEEE 802.15 working group which aims at keeping the standard's complexity and hardware cost low in order for it to be suitable for constrained devices such as sensors and actuators. [71]

Physical layer

The physical layer of the IEEE 802.15.4 standard controls the activation/deactivation of the radio transceiver, data reception/transmission, channel frequency selection and channel energy detection and is also responsible for checking whether the communication channel is occupied by a transmission or not, referred to as Clear Channel Assessment (CCA).

The communication range for 802.15.4 devices spans from 10 to 100 meters depending on the physical layer mode (the standard defines as many as 15 PHY modes) and the environment. Communication is achieved by radio transmission at one of the following license-free bands: 868-868.6 MHz (Europe), 902-928 MHz (North America) or 2400-2483.5 MHz (ISM band).

Media Access Control

When a device wants to send a packet it needs a means of knowing whether the other device is ready to receive said packet or not, this is where the MAC layer comes into play. It manages the access of the physical channel and requests a CCA check before allowing a packet to be sent. If the CCA indicates a transmission is taking place, the MAC postpones the transmission for a set amount of time before trying again. If no transmission is taking place when the CCA check is made, the MAC transmits the packet immediately.

Apart from the management of the physical layer the MAC also provides acknowledgement of frame reception and validation of incoming frames. Furthermore it natively supports three network topologies: star, mesh and cluster tree. But these are rarely used in practise as most protocols which build upon the IEEE 802.15.4 standard define their own networks instead.

Duty cycles are also managed in the MAC layer with the result that transceivers can be in sleeping mode up to 99% of the time, leading to a drastically improved network lifetime. [71]

Transport layer

The transport layer are responsible for the end-to-end communication over the network and breaking the message up into smaller segments to pass them on to the network layer. To make sure the quality and reliability are maintained for the end user, it also handles error management. This means that the transport layer provides a few different services like Connection-oriented communication, which refers to the technique where the hosts involves ensures that the connection is robust enough before sending the packet. This involves 'handshaking' which means sending acknowledgements before setting up the connection and making sure the packet arrives in the correct sequence. The transport layer also have services referring to Reliability, for example error detection can be implemented in the form of checksum to make sure data is not corrupted. Another service is Flow Control, which means making sure the data stream from an end device matches the receiving device's ability to buffer and process. If this does not work, the buffer on the receiving end could overflow or underrun. Multiplexing is a service referring to multiplexing several packet streams from other sources. The two primary implementations of transport layer protocols are Transmission Control Protocol, TCP, standard for the internet protocol stack and the more simple User Datagram Protocol, UDP. [73]

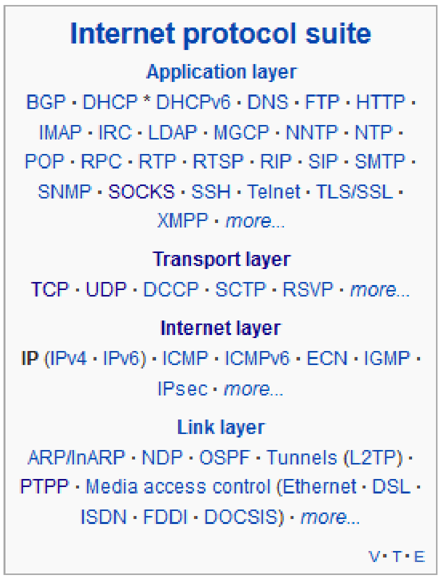
TCP is used when reliable and ordered communication is needed. The services include error-checked delivery, flow control and connection-oriented communication through handshaking. [74]

UDP are more simple TCP, and focuses on transmission rather than security. This means no handshaking or such, which means UDP cannot ensure delivery or avoiding duplication. However, by not implementing these feature UDP minimizes the packet overhead compared to TCP. [75]

3.4.3 The Internet Protocol

The Internet protocol, IP, delivers packets from the source host to the destination solely with the help of the IP addresses in the packet headers. The Internet Protocol is one of the elements that define the Internet and the dominant internetworking protocol in the Internet Layer today is IPv4. The successor to IPv4 is IPv6, the main difference being the addressing system, IPv4 uses 32-bit addresses (translates to $4.3 \cdot 10^9$ unique address) while IPv6 uses 128 bit addresses ($3.4 \cdot 10^{38}$ unique addresses).

IP is the primary protocol in the Internet layer of the Internet protocol suite, see Figure 3.7.



Internet protocol suite

Application layer

BGP · DHCP * DHCPv6 · DNS · FTP · HTTP · IMAP · IRC · LDAP · MGCP · NNTP · NTP · POP · RPC · RTP · RTSP · RIP · SIP · SMTP · SNMP · SOCKS · SSH · Telnet · TLS/SSL · XMPP · *more...*

Transport layer

TCP · UDP · DCCP · SCTP · RSVP · *more...*

Internet layer

IP (IPv4 · IPv6) · ICMP · ICMPv6 · ECN · IGMP · IPsec · *more...*

Link layer

ARP/InARP · NDP · OSPF · Tunnels (L2TP) · PTPP · Media access control (Ethernet · DSL · ISDN · FDDI · DOCSIS) · *more...*

V · T · E

Figure 3.6: The Internet protocol suite. [76]

3.4.4 The wireless embedded Internet

With the creation of IPv6, and the almost infinite amount of unique addresses, came the possibility of the "wireless embedded Internet", a part of the Internet of Things. However, the standard, IEEE 802.15.4, which was built for low-rate wireless personal area networks (LR-WPANs) does not support IPv6 out of the box and therefore work began on porting IPv6 functionality to these constrained networks. But the issues were many:

- **Packet sizes**. IPv6 requires the minimum *maximum transmission unit* (MTU) to be 1280 bytes, whereas the IEEE 802.15.4's MTU is 127 bytes. Therefore buffering and datagram fragmentation is needed which is a) a problem for IEEE 802.15.4 memory constrained devices and b) impossible since data fragmentation isn't natively supported by the IPv6 protocol.

- **Address resolution**. IPv6 nodes are assigned 128 bit IP addresses, while IEEE 802.15.4 devices use either 64 bit extended addresses or PAN-unique 16 bit addresses.

- **Difference in design**. IEEE 802.15.4 networks are prone to link failures, interference and dynamic link quality and the devices low-cost and constrained both in terms of processing power and memory. Traditional IP devices on the other hand, are larger, more costly, stationary and make use of main power supplies, resulting in differences within the network layer, which in IEEE 802.15.4 is required to be responsive and adaptive while still remaining energy efficient.

- **Routing and mesh topologies**. Routing is a two phased problem for IP-based IEEE 802.15.4 networks. Firstly, IEEE 802.15.4 does not natively support mesh topologies (multi-hop) which is common both in the IP domain and within normal IEEE 802.15.4 networks. Secondly IP routing is typically done by storing the IPv6 destination and next hop addresses in the routing headers which requires 32 bytes of memory, a solution which is impossible on constrained low-memory devices. [77]

These issues were addressed by the IETF 6LoWPAN working group and resulted in the development of the *6LoWPAN Adaptation Layer*, which successfully ports the IPv6 technology to IEEE 802.15.4 low-cost and constrained networks.

3.4.5 6LoWPAN

6LoWPAN stands for IPv**6** over **Lo**w power **W**ireless **P**ersonal **A**rea **N**etworks and is the networking technology that allows IPv6 packets to be carried efficiently within small link layer frames such as those used by IEEE 802.15.4. How this is done is presented in the sections below.

Packet sizes and header compression

IPv6 forwarding routers do not support packet fragmentation, which means that communicating hosts have to send packets with the right size (MTU). Since the IPv6 MTU of 1280 bytes is significantly larger than the IEEE 802.15.4 defined MTU of 127 bytes, a way of successfully transmitting these large IPv6 packets over IEEE 802.15.4 networks was needed.

6LoWPAN solves this by introducing a layer between the network and data link layer (see OSI-model in Figure 3.5) called the 6LoWPAN Adaptation Layer which provides the following: packet fragmentation and reassembly, header compression and data link layer routing, which means that the multi-hop relaying of fragmented datagrams is taken care of in the second layer of the OSI-model (the data link layer). [71, 77]

Routing and mesh topologies

To solve the issues related to routing, the 6LoWPAN Adaptation Layer supports routing both in the link layer (layer two) and network layer (layer three). This is referred to as 'mesh under' and 'route over' routing respectively.

In the *mesh under* set-up, no IP routing is performed in the network layer. Instead the 6LoWPAN Adaptation Layer masks the lack of a full broadcast at the physical layer, thereby emulating a full broadcasting link and compatibility with IPv6 protocols.

When utilizing a *route over* set-up however, all routing is performed in the IP layer, effectively turning each node into a IP router. This mode supports layer three forwarding mechanisms which can utilize network layer capabilities defined by IP, such as IPv6 routing or hop-by-hop option headers. Furthermore, route over constrains the IP communication to local radio coverage instead of the entire LoWPAN (as in mesh under). [71, 77]

3.4.6 Routing over 6LoWPAN

Since the specification of 6LoWPAN, routing has been one of the key issues and there have been attempts at specifying an efficient routing algorithm for 6LoWPAN-compliant IEEE 802.15.4 networks, such as Hydro, Hilow and Dymo-low. However, these proprietary solutions did not gain much momentum. Instead, a non-proprietary routing protocol, referred to as RPL and pronounced "Ripple", was proposed by the IETF ROLL working group and is now in the process of becoming the standard routing protocol for IPv6 based WSNs. [78]

RPL was developed with the following criteria in mind [79, 80]:

- **Routing tables**. Protocols which require nodes to store large amounts of routing information aren't suitable for WSNs.
- **Loss response**. Lost links in the network should be repaired locally since frequent global repairs cost too much energy and would significantly diminish the lifetime of the nodes.
- **Control cost**. The control overhead for establishing routes should be kept to a minimum while simultaneously ensuring a robust network with updated paths.
- **Link and node cost**. A WSN routing scheme must consider transmission cost and node states (memory, battery, capacity, lifetime ...) as routing metrics.

Design objectives

The RPL protocol targets collection-based networks in which nodes periodically or intermittently wake up and send data to the base station/sink node. This manner of operation is referred to as multipoint-to-point traffic and is the predominant set-up in WSNs. However, the RPL protocol also provides a mechanism for point-to-multipoint traffic as well as support for point-to-point traffic. [78]

The protocol is based on the topological concept Directed Acyclic Graphs (DAGs), which define a tree-like structure that specifies the default routes between different nodes within the WSN. However, because the protocol targets WSNs, which suffer from unreliable link quality, loss of links and noise disturbances, the DAG structure has been extended to include the possibility of a node having more than one parent. This combination of mesh and hierarchical topologies leads to a much more robust construction. On the one hand, it's hierarchical since it forces underlying nodes to self-organize based on parent-child relationships. While on the other hand, it supports the mesh topology since it allows routing through siblings, should the parents be unavailable. [78]

Furthermore, RPL DAGs are organized in such a way that the sink nodes or Internet-gateways act as the roots of the DAGs, effectively organizing the network into Destination-Oriented DAGs (DODAGs).

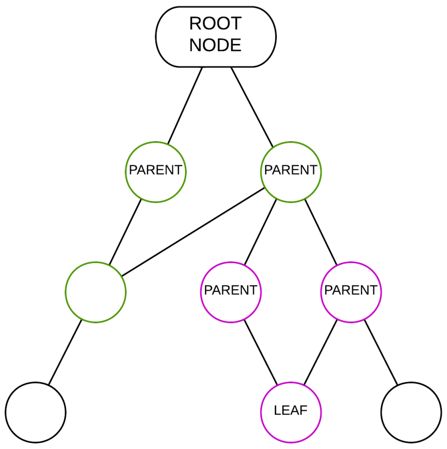


Figure 3.7: A clustered tree topology in which each node can have more than one parent.

4 Method

This section describes the engineering task of the Master Thesis, which consisted of comparing and evaluating possible hardware and software choices and constructing a functioning small scale proof of concept system. In the sections below requirements, system design and component choices are presented.

4.1 Requirements

To be able to answer the question: *"If a WSN, running an open-source operating system and communicating over 6LoWPAN, could be used in the field of autonomous irrigation?"* and before making any choices regarding the design of the proof of concept system, requirements engineering was performed in cooperation with the company representative Daniel Thysell. The aim was to capture the most important functionality (according to the company) while still maintaining a system design focus.

Irrigation as well as precision agriculture systems today suffer from power optimization and robustness issues. Therefore, these are the two main focuses through out all the design choices. If the choice stands between implementing a feature that would cost the power budget the feature need to be vital to the system or it will be discarded.

These discussions and aims resulted in the requirements below, which are divided into two areas: hardware and system. The hardware requirements handles the constraints and requirements imposed on the nodes and sensor, while the system requirements dictates minimum functionality for the network and back-end system.

Requirements

1. The sensor nodes *shall*
   - 1.1. be deterministically deployed.
   - 1.2. be able to read the soil moisture level.
   - 1.3. utilize two-way communication with the main frame.
   - 1.4. turn off redundant circuits when in idle mode.
   - 1.5. cost < € 120
   - 1.6. have a life span of at least 6 months.
2. The soil moisture sensor *shall*
   - 2.1. have a speed of measurement < 5 seconds.
   - 2.2. stay within 5% margin of error.
   - 2.3. cost < $ 100
3. The network *shall*
   - 3.1. be self-healing.
   - 3.2. utilize the 6LoWPAN protocol.

   3.3. minimize communication overhead in the transport layer.
   3.4. be scalable (1-100 nodes).
   3.5. be able to handle movable nodes (neighbour discovery).

4. The back-end system *shall*
   4.1. collect and store weather data from a local weather service going back at least 1 week.
   4.2. store data from the sensor nodes going back at least 1 week.
   4.3. make decisions regarding irrigation based on collected data.
   4.4. depending on weather/sensor data decide on sleep intervals for the nodes.

Once these requirements were settled, the system design was determined and then the suitable choices for hardware and software made.

4.2 System control loop

As mentioned in Section 2.2 and 3.3 power saving and robustness are two very important factors when designing an irrigation system. However, one is almost always chosen at the expense of the other, which makes it a balancing act in which all design decisions have to be carefully evaluated.

The overall aim of the system design was, by combining a smart irrigation system (see Section 3.1) with the WSN's dense monitoring (see Section 3.2.1), to create a closed loop system. The reason for wanting to create a closed loop system was the hypothesis that such a system could improve the performance of existing WSN solutions, both in terms of power and robustness. Furthermore, it's a rare approach (only a few existing solutions implement this [40]) in the existing technology and therefore not very well explored.

The aim of the feedback loop is to guarantee that an exact amount of water is dispersed and not an approximate amount based on a less than ideal model of the cultivated area and needed irrigation.

Existing weather based systems utilize what can be described as an open loop system, see Figure 4.1, in which the weather is used as input to the controller (which calculates the ET equations). However, the resulting soil moisture level is never confirmed (fed back into the system) or used in the calculation. The dispersed water is solely based on an ideal model of ET which assumes heterogeneity across the irrigated area. Furthermore, possible disturbances (v) are not at all accounted or compensated for.

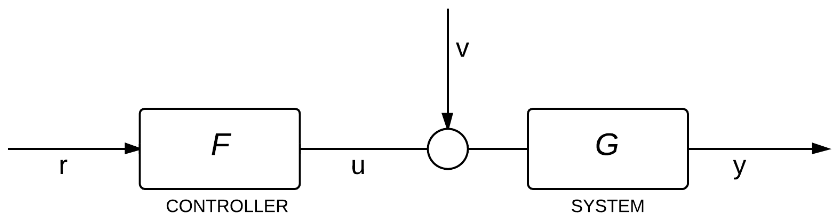


Figure 4.1: Open loop system in which irrigation is pre-determined either based on weather or soil moisture sensor data. [11]

Looking at the existing approaches on the market, and their shortcomings, it's obvious that the closed loop approach is new, not very well explored and possibly the answer to some of the drawbacks mentioned. In such a system, the actual soil moisture level would be fed back into the system (via the sensor nodes) and used in conjunction with current weather data and the ET equation to determine how much and when irrigation is needed, see Figure 4.2.

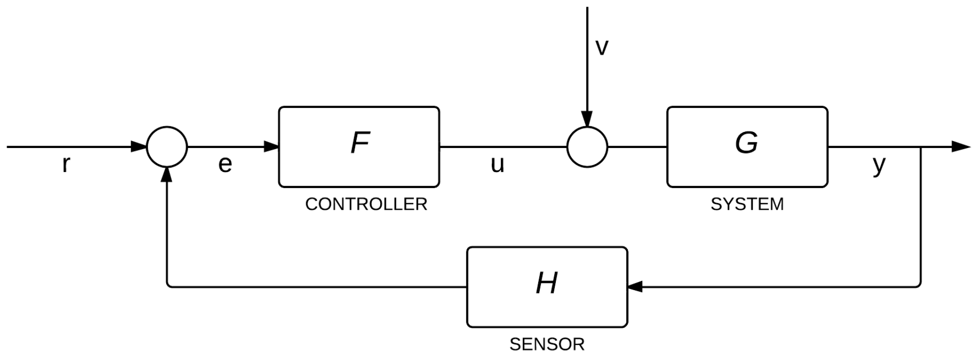


Figure 4.2: Closed loop feedback system in which the actual soil moisture level is fed back into the system, compared to the theoretical moisture level (based on ET), transformed into the corresponding irrigation needs and then evaluated against the current weather forecast. [11]

More specifically, this means that the risk for over- or under-watering is virtually eliminated since the actual soil moisture level continuously will be fed back into the system in order to adjust the needed irrigation. On top of that irrigation can be avoided when precipitation is imminent and the soil moisture level high enough to wait for the rain.

In the model in Figure 4.2 y is the actual soil moisture level (θ), r the desired soil moisture level, e the difference between the two and u the resulting irrigation needs. The discrepancy between the desired θ and measured θ (e) is then used as input to the regulator F which will compute the resulting irrigation needs after looking at weather data. With this system design, the aim is to minimize water and power usage (since pumps won't be used unless absolutely necessary).

It is this closed loop feedback system that acts as the foundation of all further design choices. Choices that will be discussed, motivated and evaluated in the coming sections.

4.3 Node specifications

To meet the requested specifications in the requirements, market research was conducted regarding both node software and hardware. As some hardware requirements limits software and vice versa (not all nodes support 6LoWPAN out of the box) these choices were made more or less simultaneously. But since the company requested an IPv6 compliant system, the software was researched first.

4.3.1 Software choices

The choice of software for the physical system was heavily affected by the company's profile within embedded systems and Internet of Things, as the core of IoT is IP compliant software. A quick market survey was conducted, which narrowed down the available choices to Contiki and TinyOS. Both operating systems support 6LoWPAN by implementing their own version of the uIP | micro IP stack, uIPv6 and BLIP respectively, but they differ in other areas. For a quick overview of the core functionalities, see Table I below.

Table I: Comparison between Contiki and TinyOS.

Evaluation criteria	**Contiki**	**TinyOS**
Language	C	nesC
Concurrency	Multi-threaded	Event-driven
Power management	Sleep modes	Sleep modes
Multitasking	Optional pre-emptive	Non-pre-emptive
Linking	Dynamic	Static
Simulator	COOJA	TOSSIM
Active community	Yes	Yes

The main differences between the two operating systems lies in the way they handle concurrency.

Contiki is written in C and has implemented so called protothreads, a stackless lightweight thread which is a mix of features from both multi-threading and event-driven programming. The kernel invokes the protothread of a process in responds to internal or external events, for example a fired timer or incoming radio packets from a neighbour. These protothreads are cooperatively scheduled which means that the process must always explicitly yield control back to the kernel at regular intervals. [81]

TinyOS programs are built out of software components, some of which present hardware abstractions. Components are connected to each other using interfaces. TinyOS provides interfaces and components for common abstractions such as packet communication, routing, sensing, actuation and storage. While being non-blocking enables TinyOS to maintain high concurrency with one stack, it forces programmers to write complex logic by stitching together many small event handlers. To support larger computations, TinyOS provides tasks, which are similar to a deferred procedure call and interrupt handler bottom halves. A TinyOS component can post a task, which the OS will schedule to run later. Tasks are non-preemptive and run in FIFO order. [82]

Since the company had experience with Contiki from earlier projects, and TinyOS and Contiki are so similar in performance, it was decided to go with Contiki. However, the implemented operating system was TinyOS. Motivation for this switch is made in the Discussion, see Section 8.3.1.

Simulation software

In order to implement and properly evaluate the behaviour of a routing protocol with a requirement on scalability, three sensor nodes (as in the proof-of-concept system) won't suffice. The difference in behaviour for two sensor nodes utilizing direct transmission or RPL will be minor and won't provide any useful insight into the performance of the routing. Therefore, it was decided to utilize a simulation tool. With such a tool any number of nodes could be deterministically deployed several meters apart, spanning a large are corresponding to an actual deployment site. Furthermore, metrics such as packet loss ratio, routing table overhead and communication overhead (for example) can easily be displayed, stored and analysed.

The two simulators, COOJA and TOSSIM (Contiki and TinyOS respectively) have similar functionalities but COOJA supplies a very user friendly GUI whereas TOSSIM is run through the Python interpreter. This helped COOJA's case when choosing the operating system and ensured a way of verifying scalability.

Furthermore, both COOJA and TOSSIM can be configured to run with hardware deployed code specifically to verify that written code and solutions scale as expected. [83, 84, 85]

Another advantage of COOJA is the fact that it enables cross-level simulation. That means that the nodes tested in this environment can be analysed in three different ways: networking (or application) level, operating system level or machine code instruction level. This enables the user to change the analysis approach of the system, optimizing the power savings and algorithms of the final network [85].

Due to issues that arose along the way, the simulating software was neither implemented or used (See Section 8.3.3.

4.3.2 Routing protocol choice

When constructing a closed loop feedback system, as mentioned in Section 4.2, one of the first things to consider is the manner in which the sensor data will travel from the nodes to the back-end (controller). In Section 3.3.2 and 3.3.4 a cluster based routing scheme is proposed as the best solution.

Since the task was not to build a routing protocol from scratch (see Section 1.4 *Scope*), two TinyOS built-in routing protocols were chosen for evaluation, namely TinyRPL (clustered tree protocol, see Section 3.4.6), and Active Message (direct transmission, see Section 2.2.5).

TinyRPL is the better protocol as proven in Section 3.3.2 but since the first goal was to setup the feedback loop, AM (Active Message) was implemented first since it seemed more straight forward. The aim was then to replace it with TinyRPL. A short comparison between the two protocols can be seen in Table II.

Table II: Routing Protocols implemented in TinyOS. [86][87]

Evaluation criteria	**TinyRPL**	**Active Message**
Characteristics		
Network topology	Tree	Star
Routing protocol	Clustered tree	Direct transmission
Max packet size(byte)	127	39
Transport layer	UDP	UDP
Requirements		
Self-healing	Yes	No (not needed)
6LoWPAN support	Yes	No
Minimize overhead	Yes	Yes
Scalable (1-100)	Yes	Yes*
Neighbour discovery	Yes	No**

*scalability depends on signal strength (i.e. hardware dependent).

**since no packets are forwarded neighbour discovery is unnecessary.

As can be seen in Table II, TinyRPL utilizes 6LoWPAN, and fulfils all the requirement specified for the network. AM falls short on a few points, the most important ones being routing protocol and 6LoWPAN support.

Once the feedback loop was constructed and it had been confirmed that data was traversing the system as expected the choice was made to switch to TinyRPL. However, due to issues discussed in Section 8.1.3, this turned out to be impossible. The proof-of-concept therefore continued using Active Message.

4.3.3 Hardware choices

The hardware for large scale deployments of WSN should be low-cost, robust and support the current state of the art operating systems. Since software at this point already had been chosen, the hardware choice was narrowed down to nodes that supported Contiki. However, there were still 31 platforms to choose from. Since the company had worked with the Zolertia Z1 node before and specifically in a related project the choice leaned heavily from the beginning towards choosing those sensor nodes. However, a quick background study was conducted anyway in which the most popular and common sensor nodes were evaluated, Table III below.

Table III: Characteristics of the TMote Sky, IRIS and Z1 sensor nodes [27, 28, 29].

Evaluation criteria	TMote Sky/TelosB	Crossbow IRIS	Zolertia Z1
Processor			
MCU	TI MSP430F1611	Atmel ATmega1281	TI MSP430F2617
VCC	1.8 ... 3.6 V	2.7 ... 3.6 V	2.1 ... 3.6 V
Flash	48 kB	128 kB	92 kB
RAM	10 kB	8 kB	8 kB
ADC	12 bit	10 bit	12 bit
Current draw: Active	0.5 mA @ 1MHz	8 mA @ 4MHz	0.5 mA @ 1MHz
Current draw: Sleep	2.6 uA	8 uA	0.5 uA
RF Transceiver			
Radio chip	TI CC2420	Atmel RF230	TI CC2420
Data rate	250 kbps	250 kbps	250 kbps
Transmission power	0 : –25 dBm	0 : –24 dBm	0 : –25 dBm
TX range outdoors (0 dB)	125 m	> 300 m	180 m (antenna)
Current draw: RX	19.7 mA	16 mA	18.8 mA
Current draw: TX	17.4 mA @ 0dBm	17 mA @ 3dBm	17.4 mA @ 0dBm
Current draw: Sleep	1 uA	1 uA	< 1 uA
Electromechanical			
GPIO	16 pin	51 pin expansion	52 pin
Onboard sensors	3	-	3
Power supply	AA/USB	AA/USB	AA/micro USB
User interface	1 button, 3 LEDs	3 LEDs	1 button, 3 LEDs
Cost	€ 77	€ 85	€ 95

As can be seen in III the sensor nodes do not differ much in actual hardware specifications. That together with the following facts:

- The MCU's has an ultralow current draw and is specifically designed for low power purposes. [88]
- It has an integrated temperature sensor [27], which expands the available data input to the irrigation decision.
- The integrated battery pack, making it standalone.
- It was readily availability online.
- The MCU and RF transceiver (MSP430 and CC2420) are recurrent in the WSN field.

is why the Zolertia Z1 node was chosen.

4.3.4 Soil moisture sensor

The fully developed solutions for smart irrigation on the market are many, but as to the availability for soil moisture sensors are few. There are, however, several ways to measure the moisture in soil.

1. **Electrical conductivity probe:** The probe measures the electrical resistance between two electrodes. Wet soil has better conductivity, and therefore a higher reading is achieved. The electrodes have direct contact with the soil, which makes them more sensitive to salinity and pH. There is a possibility for oxidation on the electrodes, so the probe needs regular maintenance. The probe needs calibration in every new type of soil, this again caused by the high sensitivity. Apart from these flaws, the probe is often cheap and easy to attain online. [89]
2. **Electrical resistance block:** The block measures the conductivity in the soil, just like an electrical conductivity probe. The difference is that this sensor electrodes are embedded in gypsum or sand-ceramic mixture. A case made of fiberglass or perforated metal is also common. This makes the electrical resistance block much less sensitive to outer factors. [90]
3. **The Fringe Capacitance Sensor:** Consists of two electrodes separated by a dielectric material, a material which works as an insulator, but can be polarized with an electrical field. When a high oscillating frequency is applied between the electrodes and a resonance frequency can be measured. This resonance frequency is proportional to the capacitance, which increases as dielectric constant (a soil property) changes as the moisture content of the soil increases. [91]
4. **TDR:** or a Time-Domain Reflectometer uses a short electromagnetic pulse along a conductor, which reflects and is measured to determine the moisture level. The speed of the pulse decreases as the dielectric constant changes and the moisture increases. The technique is expensive, but provides high accuracy. [89]

Table IV: Characteristics of the VH400, Watermark and SEN0114 Soil Moisture Sensors [92, 93, 94]

Evaluation Critera	**VH400**	**Watermark**	**SEN0114**
Price	$ 37.95	$ 38.00	$ 4.80
Technology	4.	2.	1.
Supply Voltage	3.3-20VDC	AC	3.3V, 5V
Output Voltage	0-3V	0-3V	0∼4.2V
Current Cons.	<7mA	-	35mA
Response Time	400ms	65s	-
Accuracy	2% at 25°C	-	-

Moisture sensor choice

As the supply of soil moisture sensors online were limited, the choice was decided between three different probes, see Table IV. Unfortunately, the Watermark sensor, an electrical resistance block, required AC. This requirement was seen as too difficult to implement on the Z1, and the probe was therefore rejected. Also, the readings for this probe took around 65 seconds before the instrument would give accurate results, an unacceptable time frame.

The price on the SEN0114 made it worth to consider even with the disadvantage of the probability of oxidation and needed calibration. However, due to the company's previous encounter with this kind of sensor, they recommended against it, as the output was too unreliable.

The choice fell on the VH400, with good response time, within the price range and the best documented current consumption.

4.4 Back end

The back end of the system needed to collect and store node and weather data, perform computations on stored data, make decisions and instruct the sink node. The front end of the system needed easy access to database data and an easy and straight forward way of presenting that data. A number of different options were thereby recommended by an expertise within the company, namely the MVC frameworks: Django (Python), CodeIgniter (PHP) and Ruby on Rails (Ruby).

PHP was considered because of the IPv6 functionality. With PHP it's easy to build a web server which can communicate directly with the nodes over IP. But since the project participants didn't have that language competence it was concluded that it would be too time consuming to implement and instead the choice was made to stick to Python but learn how to use the Django framework. Furthermore, the company supervisor had extensive knowledge in Django development.

Django ships with a built in SQLite database (which is file-based) but can be configured for use with for example MySQL (which is server-based). It also comes with a lightweight, standalone web server for development and testing. [95]

4.4.1 Database choices

Since Django ships with a filebased SQLite database, but can be configured with many other database management systems, the choice stood between using the default database or implementing something more robust and well used like MySQL, Oracle etc.

However, since the aim of the thesis didn't concern web servers, frameworks or databases it was decided to go with the default SQLite while being fully aware of its shortcomings such as:

- It's file based, meaning non-robust and non-flexible. When all data is stored locally on the hard drive it leaves the system vulnerable.
- It doesn't scale well.

5 Implementation

The proof of concept system was built to answer the question: *"If a WSN, running an open-source operating system and communicating over 6LoWPAN, could be used in the field of autonomous irrigation?"* and to implement the requirements and design features discussed in Chapter 4 (Method). The purpose was to identify if the design choices were suitable for an actual implementation. The following sections in this chapter will review the choices made to finish the product.

5.1 Overall system design

The system consists of two sensor nodes, one sink node, a PC acting as the main frame and a soil moisture sensor, as seen in Figure 5.1. The final layout were made to utilize the system control loop discussed in Section 4.2. The implementation of each component will be reviewed in the following sections.

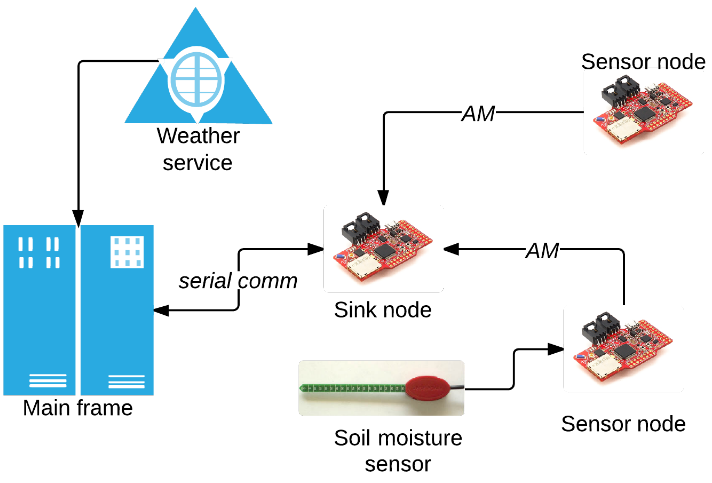


Figure 5.1: Outline for the system.

5.1.1 Node design

Node design refers to the software choices made to implement the features needed for the system to perform the wanted tasks.

Network

The communication protocol that were chosen was the standard implementation in TinyOS called Active Message. Active Message, or *AM*, is a single-hop, best-effort communication packets that generates the node addresses from a pre-programmed node id. Therefore the node id of the sink node, which acts as a base station are to be pre-programmed into all the sensor nodes. The nodes communicated with the sink node through unicast and vice versa, meaning no other than the designated receiver read the sent message.

Sensor node

The sensor nodes primary objective was to gather soil moisture data and forward it to the main computer frame. The decision making process can be observed in Figure 5.2. The timer was set according to a predetermined sampling frequency. To make sure the node didn't waste any unnecessary energy, all peripheral components was shut off when the node was idle, i.e entered sleep mode. One of the main power reduction techniques for MCU is shutting off the components that aren't needed, and therefore the implementation of said technique is important for all systems trying to save power, see Section 3.3.6. As the system characteristics implies that $T_{sleep} >> T_{active}$, the assumption was made that the system should enter the lowest power mode possible (see Equation 3.18).

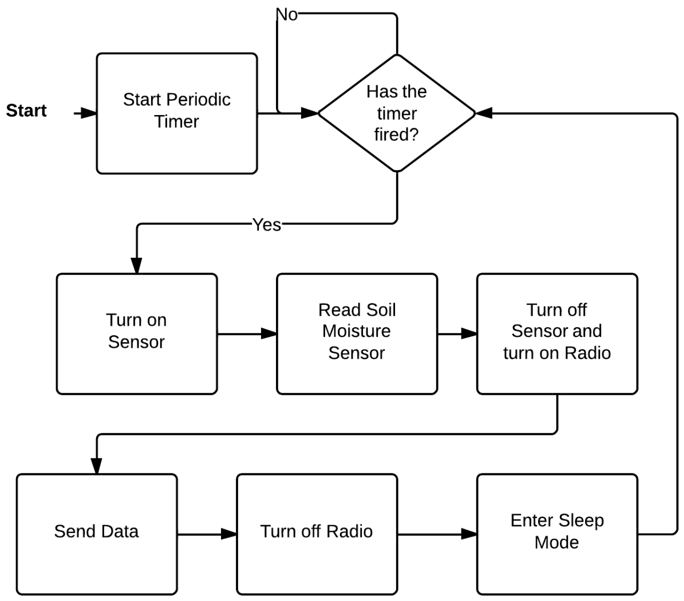


Figure 5.2: The decision making process for a node.

The MCU in the Z1 node, MSP430, utilizes 5 different power modes, where the lower the power mode, the less clocks are turned on, see Table II. As the design utilizes a sleep timer for the node to wake up, the node needs to be able to receive an interrupt from a clock. The Auxiliary Clock, *ALCK* can be sourced from a 32kHz watch crystal, and is the only clock that is active in the Low Power Mode 3, *LPM3*, see Table II [67, p. 19]. Therefore the node sleep interval was decided by a timer that utilizes said 32kHz watch crystal. By calling the predefined API *MCUSleep*, which evaluates how many of the peripheral components that are active and puts in the appropriate low power mode, the node didn't waste energy on components that weren't used. As the system did not have any strict deadlines due to the characteristics of the system, the CPU were set at the lowest available pre-defined speed at 1MHz. Another argument to use the lowest predefined setting was due to the argument done in 3.3.6.

Soil moisture sensor

The soil moisture sensor utilized the 12-bit ADC conversion available on the MSP430 to convert the input voltage from the VH400 to digital readings [67]. The voltage supply were V_{cc}+3V [92].

The output given from the sensor were in the range of 0-3V, and could be recalculated to soil moisture content θ by calibrating the sensor. However, the output voltage from VH400 corresponding to θ is not linear, but can be converted depending on which segment the output value corresponds to, see Table I.

Table I: Simulation results.

Voltage Range V_{out}	**Equation for** ϵ
$0 - 1.1V$	$10 \cdot V_{out} - 1$
$1.1V - 1.3V$	$25 \cdot V_{out} - 17.5$
$1.3V - 1.82V$	$48.08 \cdot V_{out} - 47.5$
$1.82V - 2.2V$	$26.32 \cdot V_{out} - 7.89$

ϵ is the relative converted soil moisture value. After the conversion according to Table I, the soil moisture could then be expressed as

$$\theta = \frac{\epsilon}{\epsilon_{max}} \tag{5.1}$$

where ϵ_{max} is maximum converted value when the soil is fully saturated.

Sink node

The purpose of the sink node was to gather the data from the sensor nodes and forward the messages to the main computer frame and vice versa. An illustration of the data flow is depicted in Figure 5.3. As the sink node was connected on the power grid through the main computer frame, there was no need to limit the functionality for power saving purposes. Therefore the listening processes on both the UART and the radio was active at all times. This was also to prevent the system from losing any packets.

5.2 Back-end functionality

The back-end system was run in an Ubuntu 12.04 Precise Pangolin environment upon which TinyOS and Django have been installed. To integrate Ubuntu with the computers provided by the company, the operating system was installed using the open-source virtual environment VirtualBox. The task of the back-end PC is to connect to a local weather service, download the 5-day forecast, store it in a database, analyse it together with the collected and stored sensor data and then make decision on irrigation, see flowchart in Figure 5.4.

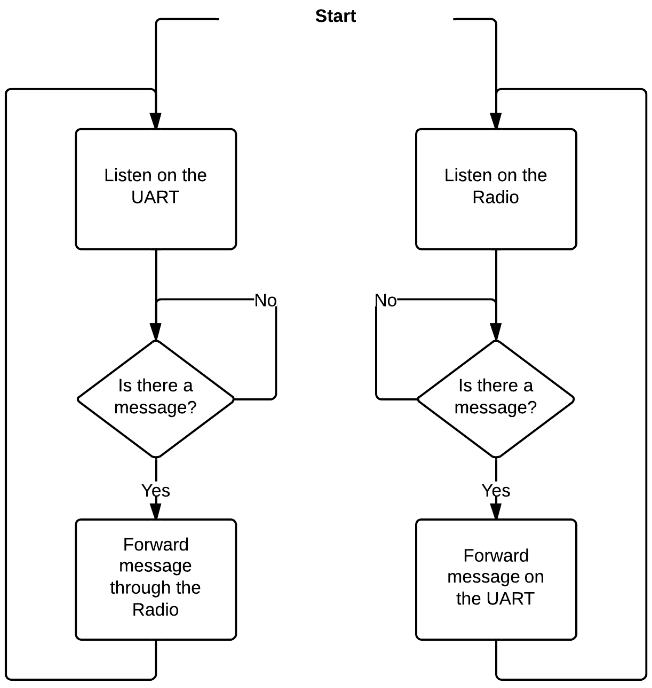


Figure 5.3: The decision making process for the sink node.

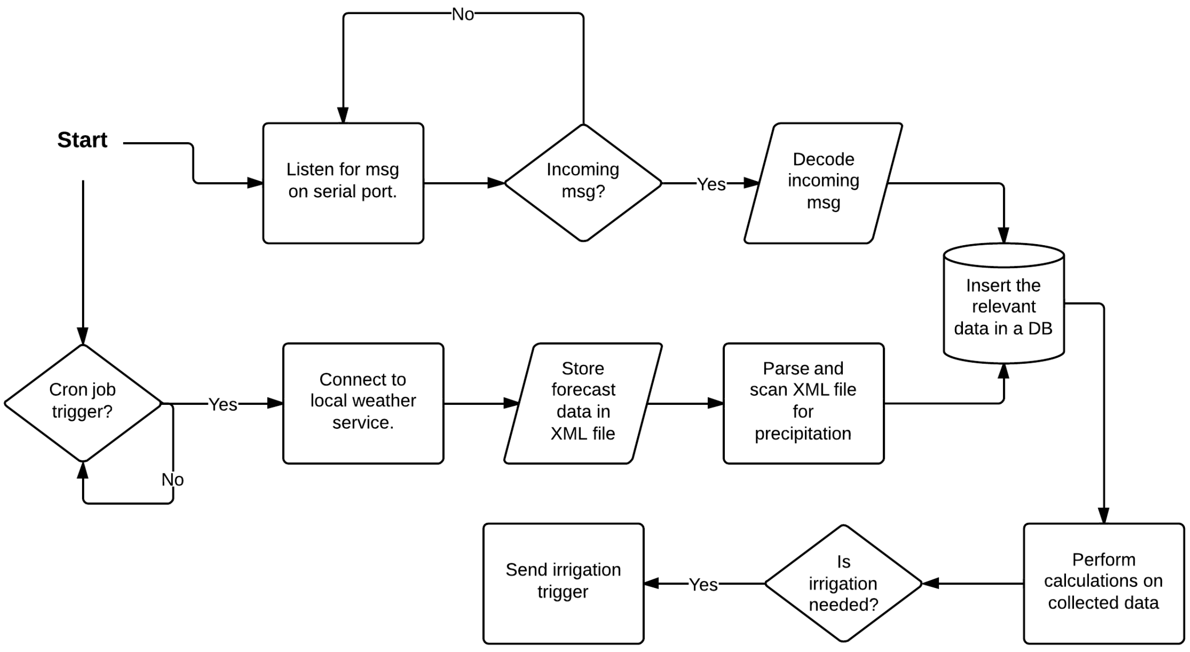
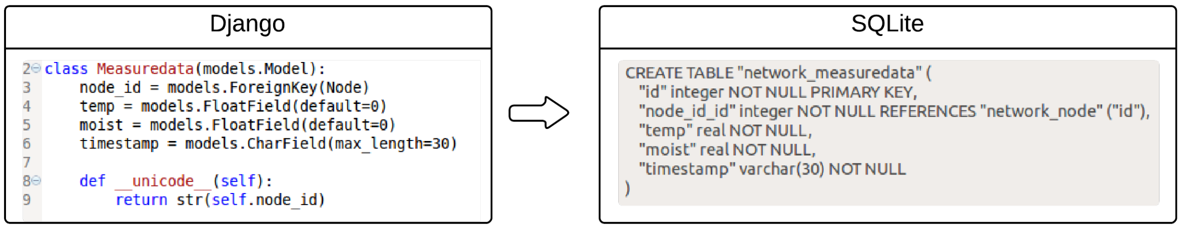

No
Start
Listen for msg on serial port.
Incoming msg?
Yes
Decode incoming msg
Insert the relevant data in a DB
Cron job trigger?
Yes
No
Connect to local weather service.
Store forecast data in XML file
Parse and scan XML file for precipitation
Send irrigation trigger
Yes
Is irrigation needed?
Perform calculations on collected data

Figure 5.4: A flowchart of back-end code.

5.2.1 Database configuration

Django ships with a built in SQLite database in which tables were created with Django models. This meant creating classes in Django models which were then translated into SQL code which ultimately created the database structure, see Figure 5.5.



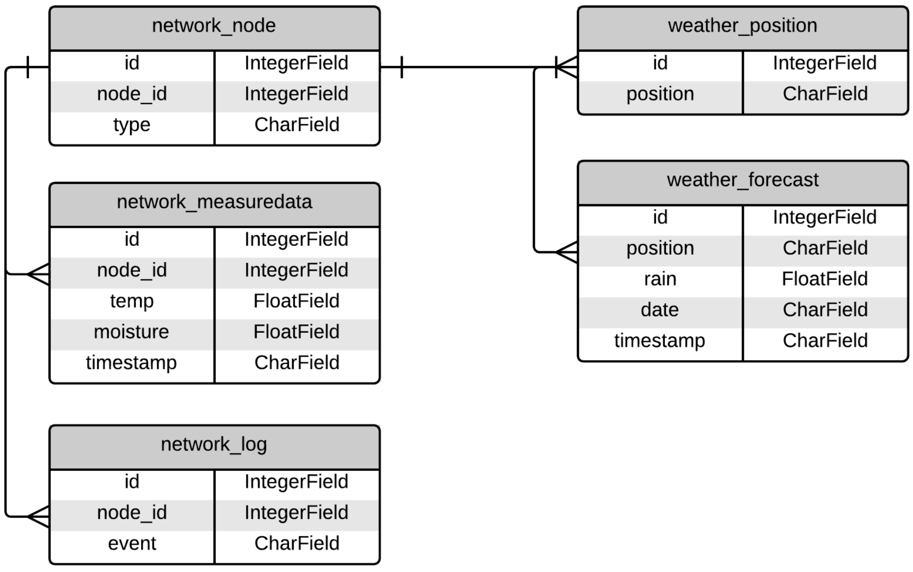
```python
class Measuredata(models.Model):
    node_id = models.ForeignKey(Node)
    temp = models.FloatField(default=0)
    moist = models.FloatField(default=0)
    timestamp = models.CharField(max_length=30)

    def __unicode__(self):
        return str(self.node_id)
```

```sql
CREATE TABLE "network_measuredata" (
  "id" integer NOT NULL PRIMARY KEY,
  "node_id_id" integer NOT NULL REFERENCES "network_node" ("id"),
  "temp" real NOT NULL,
  "moist" real NOT NULL,
  "timestamp" varchar(30) NOT NULL
)
```

Figure 5.5: How Python code is translated into SQL by Django.

Django also automatically creates an admin interface on the web server, which allows the user to login with a created superuser account and then modify the content of the database tables by manually adding data. This allows for early and continuous testing of the tables, data definitions and general structure of the database, which was a great advantage. The final structure of the database can be seen in Figure 5.6.



network_node	
id	IntegerField
node_id	IntegerField
type	CharField

network_measuredata	
id	IntegerField
node_id	IntegerField
temp	FloatField
moisture	FloatField
timestamp	CharField

network_log	
id	IntegerField
node_id	IntegerField
event	CharField

weather_position	
id	IntegerField
position	CharField

weather_forecast	
id	IntegerField
position	CharField
rain	FloatField
date	CharField
timestamp	CharField

Figure 5.6: The structure for the Django created SQLite database.

5.2.2 Weather data collection

The algorithm for the dynamic sleep intervals utilize weather data as a parameter when calculating the length of the sleep periods. This meant creating a script which could connect to an online weather service, download the data to an XML file, parse the file while scanning it for requested data and then put it in the Django database. Another calculation script would then query the database, compute the needed variables and forward the information, via the sink node, to the sensor nodes.

The weather script is written in Python, connects to yr.no and downloads the requested weather data. Since the script needs to renew the downloaded weather data at a certain rate, to make sure calculations aren't made on outdated information, cron was used to schedule the execution of the script. Cron is a time-based job scheduler which is native to Unix/Linux-based operating systems and thereby also to VirtualBox. The interval 24 hours was chosen since it was concluded that weather forecasts, albeit unpredictable, don't change fast enough to require more frequent monitoring.

The forecast service *yr.no* was used since it provides a very user friendly API for accessing and downloading weather forecasts, namely in the form of a URL (*http://www.yr.no/place/LOCATION/varsel.xml*) in which *LOCATION* is simply replaced with the desired location. Furthermore, the service is completely free and although there are limits to how often data can be accessed and downloaded, those are much higher than the frequency of data updates needed for this thesis.

The script used for querying the database and handling the communication with the sink node was written in Java.

6 Analysis

When designing a complete and robust wireless sensor network, aimed at precision agriculture, specifically irrigation, there are, as shown in this report, many things to take into consideration. Out of all the different parameters to tweak and look further into, the following two have been chosen for further analysis:

- Network design
- Weather data usage

The following sections will go through the chosen approaches for the thesis and implementation, analyse the outcome and discuss the reliability of the methods used.

6.1 Network design

As mentioned in the Theory 2 chapter there are many aspects to take into account when designing, building and implementing a wireless sensor network aimed at precision agriculture, specifically irrigation. Out of the literature and previous research done in the field ([7, 5, 6, 9, 54, 55]) very few put much, if any, effort into the power management aspect of the network design. Furthermore, there is a trade-off between power management and robustness that for every given WSN implementation needs to be addressed.

As presented in the State of the Art chapter, the cluster based protocol MOECS is at the forefront of robust and power aware routing. However, such an IPv6 compliant protocol has yet to be developed for IEEE 802.15.4 devices.

Thence, this chapter will provide analytical test results from MATLAB-calculations based on the First Order Radio model. The aim is to establish whether the MOECS protocol possibly could outperform the TinyRPL protocol. Therefore both protocols are assumed to be sending packets of the same size in the following calculations (the MTU frame size of IEEE 802.4.15 which is 127 octets).

As mentioned in 4.3.1 (*Method*) simulations software should have been used for evaluation but as discussed in 8.3.3 that was not possible. Furthermore, as discussed in 8.1.3 TinyRPL (the TinyOS implementation of RPL) could not be implemented due to hardware issues. Despite all this there was still interest from the company to provide some kind of evaluation of the behaviour of TinyRPL, as it is the natural progression of the assembled proof-of-concept system (once the hardware has been replaced).

6.1.1 TinyRPL vs. MOECS

As mentioned in the Section 3.3.2 there exists a threshold at which a multi-hop architecture starts to consume less power than direct transmission. In order to assess which type of protocol should be used in terms of power consumption, a test bed was constructed and the following assumptions made:

Assumptions:

- All sensor nodes are stationary and homogeneous in terms of energy, communication and processing capabilities.
- Nodes are dispersed deterministically in a 2-dimensional space.

- The sink node is located outside the deployment region and has no energy constraints.
- Nodes are location unaware i.e. they are not equipped with any GPS device.
- Radios can expend the minimum energy to reach the intended recipients by controlling the radio range.
- Both protocols send packets of the same size: the MTU of the IEEE 802.15.4 standard, 127 octets.
- The connectivity between nodes are uniform, meaning the link quality from A to B is equal to that between B and A.
- The First Order Radio model is used to calculate the dispensed energy.

With these assumptions and the requirements in Section 4.1 in mind, the following test bed was constructed:

- 64 sensor nodes
- 1 sink node
- All sensor nodes were uniformly deployed in a grid pattern, 8 x 8
- The inter-node distances was 10 meters
- The entire area covered was 0.5 hectare land

The reason for choosing $\sim$ 60 nodes 10 meters apart stems from the earlier research conducted in [6, 7, 5, 9, 55], according to which a large WSN deployment correlates to $\sim$ 60 nodes. The only existing larger test bed is the LOFAR-agro project which deployed 110 nodes, spaced approx 15 meters apart, covering approximately 2.25 hectare land.

Regarding the inter-node distances, the choice of 10 meters is a result of the earlier work conducted, such as in [6, 7, 5], in which a mean distance of about 10-15 meters was used. The reason for the short distances was both the aim of dense monitoring (precision agriculture) but also the fact that all earlier studies ran into quite heavy connectivity issues between nodes. The existing test bed is visualized in Figure 6.1.

The first thing to conclude, was whether to exclude direct transmission as a viable option (the protocol the small proof-of-concept system was using). As presented earlier in 3.3.2, direct transmission requires less energy than multi-hop if the following equation holds true:

$$E_{direct} < E_{multi-hop} \tag{6.1}$$

$$E_{elec} + \varepsilon_{amp} n^2 r^2 < (2n-1)E_{elec} + \varepsilon_{amp} n r^2 \tag{6.2}$$

$$\frac{E_{elec}}{\varepsilon_{amp}} < \frac{nr^2}{2} \tag{6.3}$$

Since the average distance between nodes in the test bed is 10 meters and the average hop-depth 4 (see the test bed in Figure 6.1) the result will be the following:

$$\frac{50 \cdot 10^{-9}}{100 \cdot 10^{-12}} < \frac{4 \cdot 10^2}{2} \Longrightarrow \cancel{500 < 200} \tag{6.4}$$

In other words, direct transmission will cost more than multi-hop in the existing set-up. The aim now is to compare the existing state of the art routing scheme for IPv6 compliant networks, TinyRPL, to the, not yet IPv6 compliant, protocol MOECS. Whether or not to adhere to the growing IPv6 standard within WSN is a decision that has to be made with the implementation in mind. Needless to say, the possibilities are much greater when choosing an IPv6 compliant network and routing protocol but might also cost the power budget. Normal packet-frames in TinyOS for AMpackets are 39 bytes, whereas the IPv6 packets are a whopping 127 bytes. That means that for transferring just one packet 10 meters, the consumed energy for sending the IPv6

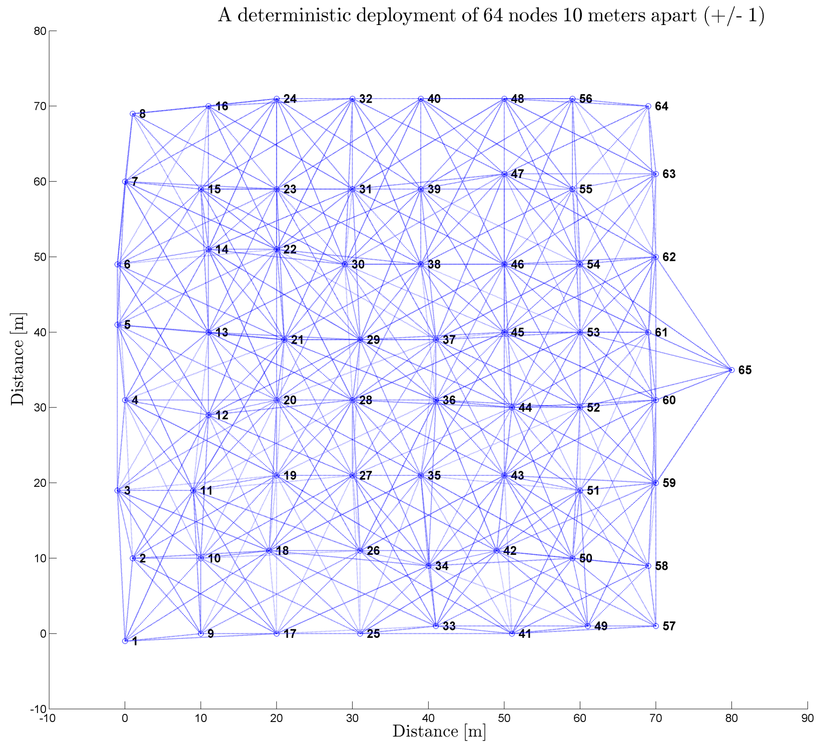

A deterministic deployment of 64 nodes 10 meters apart (+/- 1)
Distance [m]
Distance [m]
65

Figure 6.1: The constructed test bed with 64 sensor nodes and 1 sink node, distributed in a 8 x 8 uniform grid.

packet is almost 2.3 times larger than for the AM-packet (see Equation (3.2)). However, when the distance is increased to 25 meters the consumed energy is 1.4 times larger than for AM-packets.

So if the aim is simply to lower the power consumption it's not certain that IPv6 is necessary, depending on the distance the packets have to travel, as shown in Equation (3.2)) where communication distance is the most important parameter.

After having ruled out direct transmission, the two protocols were evaluated separately. A cluster of 16 nodes in the south-west corner of the test bed was chosen for analysis.

In the first scenario, concerning MOECS, see Figure 6.2, 15 nodes collect and send their data to the CH which aggregates and forwards the data to the sink node. With the help of the first order radio model the resulting energy costs was calculated to 2.5161 mJ for the entire cluster, meaning 15 sending/receiving operations and one long distance transmission to the sink node from the CH. The cost for a single packet to be transmitted from a node via the CH to the sink node is 362.81 µJ.

After having evaluated MOECS, a TinyRPL scenario was constructed, in which the path from node to sink looked much different and includes more hops along the way, see Figure 6.3.

The blue connections represents the one hop neighbour of each node in the tree and the red thread a possible route through the tree structure in which each node transmits as far as it can reach in each step. With this approach the energy cost for one packet is 695.25 µJ and for all the 16 nodes in the south west corner the cost would be 7.3353 mJ.

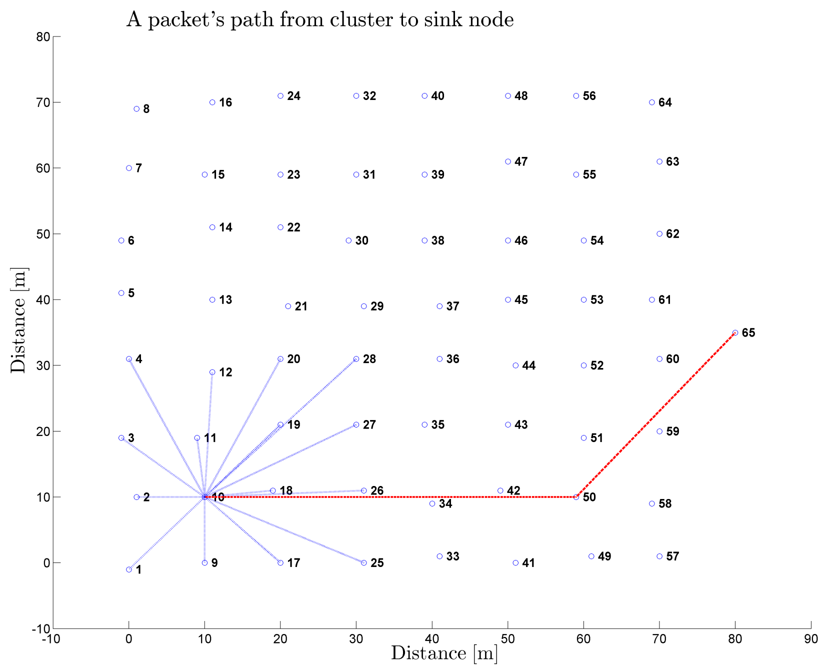


Figure 6.2: An example of 15 leaf node reporting their data to the current CH which in turn forwards the aggregated data, via another CH, to the sink node.

These preliminary results suggest that there are indeed power consumption improvements to be made by switching to or implementing a clustered protocol over a tree protocol.

Table I: Simulation results.

Scenario	Cluster	Tree
TX/RX of 1 data packet	362.81 µJ	695.25 µJ
TX/RX of 16 data packets	2.5161 mJ	7.3353 mJ

As a comparison, the cost for 1 packet transmission in direct transmission is 828.04 µJ and for a complete round of direct transmission for the entire test bed the total consumed energy is 1.1355 J.

These results and their reliability are discussed in Section 8.1.3.

6.1.2 Data aggregation

In both protocols mentioned above, data aggregation plays a big part in making the protocol efficient. Instead of simply forwarding the messages through the tree structure, each node adds their own data as they forward the message to the sink. Same general idea goes for the cluster based algorithm, in which the CH collects and aggregates the cluster data into one message which is then transmitted to the sink.

The interesting part becomes how to make sure unnecessary data isn't appended to a message or forwarded as a part of the CH message. Furthermore, both erroneous and redundant data

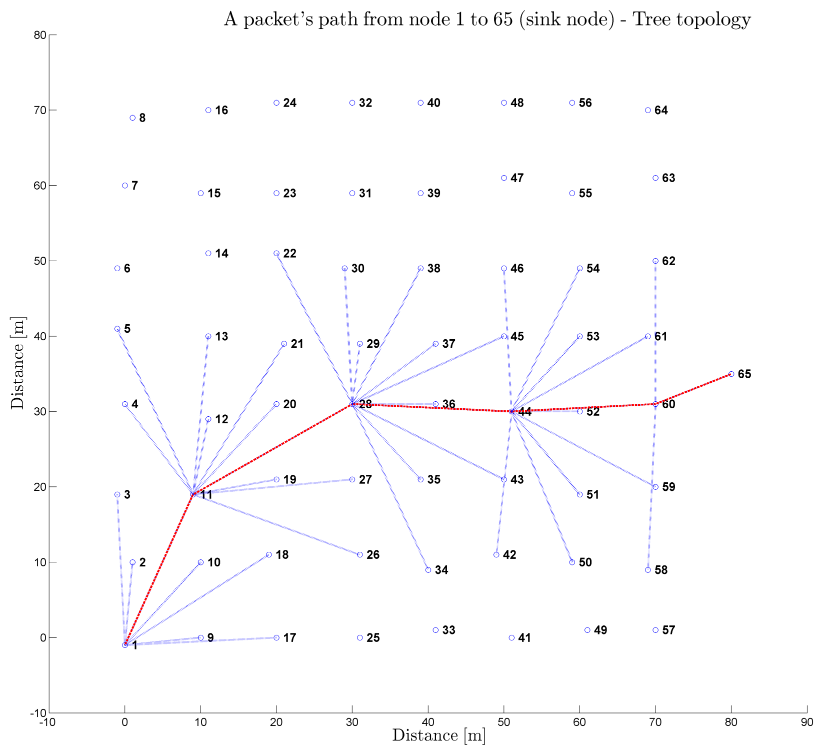


Figure 6.3: An example of a possible route through the network when utilizing a tree protocol.

must be avoided.

For this, there are several approaches. The error and redundancy check can be made at the sink, which has no power constraints and thus it won't deplete the nodes' energy. However, the cost for sending and receiving all the unnecessary data must then be taken into consideration. A smarter approach, is the distributed one, in which each sensor node has an agent which locally sorts out the erroneous data and checks for data redundancy when adding data to a packet or aggregating cluster data. Furthermore, the agent limits the communication if only irrelevant data is present, thereby minimizing the communication costs.

As always with WSNs, memory and processing power is limited and using the external flash to store older measurements as comparison costs valuable energy.

6.2 Dynamic Sleep Intervals

As mentioned in Section 3.1.1, most smart weather-based systems schedules irrigation by predicting how much water will be depleted from the soil and then compensates that water loss with irrigation. This relationship between irrigation and water depletion, evapotranspiration, is expressed in Equation (2.2). If a soil moisture sensor is used as well as weather data analysis, the initial values of $\Delta\theta$ can be acquired, like the closed-loop solution suggested in Section 4.2. The sensors will also give feedback to the ET-calculations, so they can be validated [40]. If the irrigation is scheduled for a time t, and I_0, R_0 and θ_0 is the values when $t = 0$ and I_1, R_1 and θ_1 is the values for $t = T$ then:

$$\frac{\theta_1 - \theta_0}{T} = -ET_C + \frac{I_1 - I_0}{T} + \frac{R_1 - R_0}{T}, \tag{6.5}$$

where the assumption that both rain R and irrigation I is added instantaneous is made. If $R = 0$, $I = 0$ and ET_C is constant, Equation (6.5) can be simplified and generalized for all $t > 0$ as

$$\theta_1 = -ET_C \cdot t + \theta_0. \tag{6.6}$$

and visualized in figure 6.4. The soil moisture θ has to stay within the limits mentioned in Equation (2.5), where θ_{MAD} is the lower and θ_{FC} is the upper limit. If the system needs to irrigate every T to prevent the soil moisture target θ to reach the lower limit θ_{MAD}, the system frequency f can be assumed to be $1/T$.

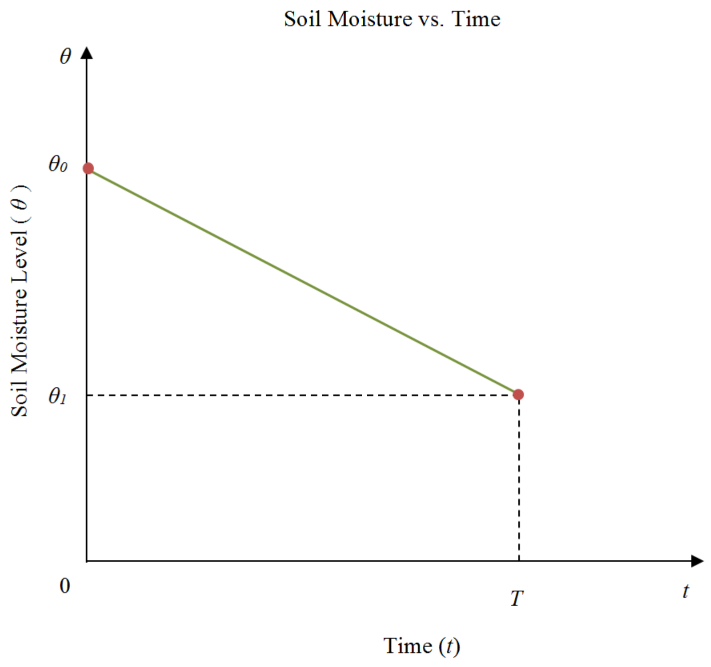


Figure 6.4: A simple representation on the relationship between soil moisture and time, affected by ET_C.

For validation of the ET_C model through a soil moisture sensor, the sensor have to sample accordingly to the system frequency. The Nyquist theorem states that

$$f \leq f_s/2 \tag{6.7}$$

where f_s is the sampling frequency. Further knowledge of the system is needed to know how often it is suitable to sample to get a stable and reliable system. However, no in-depth studies has been made on the area. Some authors like [96] suggest sampling for normal irrigation once every two days. In other sources regarding precision agriculture some authors recommend sampling once or twice every hour like the [55], up to every 15 minutes like [7, 51]. This gives some kind of indication of how much power could be saved and how the system should be designed. The trade-off here is accuracy versus power-saving. As mentioned in Section 3.2, the dense monitoring done in precision agriculture could significantly improve the system knowledge with end result being increased crop yield. However, before any in-depth study has been undertaken in the field, the system cannot be optimized.

When the sample frequency is set and the irrigation is adjusted accordingly, the unknown variable in Equation (2.2) is R, the rain. As mentioned in Section 3.1.1, a popular implementation is to shut off irrigation until the rain has stopped, to prevent over-irrigation. Can this technique be applied to the system presented in this report?

Firstly, one needs to know how much it is going to rain. Due to the weather-based implementation done with fetching forecasts through an online weather service, this data is available. On a side note; to get real-time rain data feedback, a rain sensor should be implemented. However, in this section it is assumed that the rain data provided is accurate. The assumption made is that *if* it rains, the time t between the last irrigation and next irrigation increases. This would mean that the system period T is prolonged in proportion to the duration of the rain. If $N_{samples}$ is the amount of samplings done during the period T, it could be expressed in the following Equation:

$$N_{sample} = T \cdot f_s. \tag{6.8}$$

So when keeping N_{sample} constant and increasing the system period, the sampling frequency will decrease.

6.2.1 Changing the time period

Due to one of the biggest constraints in WSN being the power, every attempt to turn off the node and/or the sensors prolongs the life span of the entire system. If the needed sampling interval increases, the node can do fewer measurements every time unit. This new sampling frequency would be expressed as:

$$f_{new} = \frac{f_s}{1 + \frac{T_R}{T}}. \tag{6.9}$$

where T_R is period when it is raining and T is the period for the system, see Equation (2.16) and Figure 2.13. If E_{cycle} is defined as the energy cost for one full node cycle, see Equation (2.16), then the energy saved E_{saved} can be expressed as

$$E_{saved} = E_{cycle} \cdot f_s T_R. \tag{6.10}$$

Equation (6.10) indicates that the longer T_R is, the more energy will be saved. The idea is therefore to dynamically change how often the sensor node is turned on to sample, i.e change for how long the system sleeps. However, as the system is designed to be used in precision agriculture, further implementation would be to utilize other sensors on each node to monitor other environmental behaviours [7, 5]. If one were to implement a temperature sensor like [7], the measurements would not be irrelevant during rain, and it might be difficult to motivate turning on the node less often when the period increases. However, the author of [97] states that it is the sensors that consume the greatest portion of node energy, when the application is precision agriculture. This means that it would still be a good idea to not utilize the soil moisture sensor as often as the other sensors when it is raining. This would be denoted as:

$$E_{saved} = E_{soilsensor} \cdot f_s T_R. \tag{6.11}$$

To make this work, the system needs to implement a feature that is not part of a normal multi-point-to-point communication routine: the main frame needs to be able to communicate back to the node. The assumption is simple, if the power saved by extending the sampling intervals is surpassed by the power to communicate said change in sampling intervals, the transition is valid. If $E_{receive}$ is the energy cost for the system to send a message a specific node, change in sampling frequency is motivated if:

$$E_{receive} < E_{saved}. \tag{6.12}$$

6.2.2 Taking precipitation into account

The aim of implementing dynamic sleep intervals is tied to the idea that completely or partially turning off the sensor measurements and/or radio communication during rainy days could lead to significant improvement in battery lifetime.

According to SMHI the average amount of days with more than 1 mm precipitation amounts to ~ 100 in Sweden [98]. As mentioned in the Section 6.2, Equation (6.10) dictates how much energy is saved during days when it's raining. What it implies is that during rainy days the number of sampling actions are kept constant as the system's time period increases, causing the system frequency to decrease, i.e. if rain is imminent 3 days ahead the periodicity of the system increases from 1 to 4 days but the number of sampling cycles remain the same and thus the frequency changes. In practise this means that 3 days worth of sampling cycles are saved. So, if it rains 100 days in a year the maximum save in energy is described by the following equation:

$$E_{saved\%} = \frac{\cancel{E_{cycle}} \cdot \cancel{f_s} T_{rain}}{\cancel{E_{cycle}} \cdot \cancel{f_s} T_{year}} = \frac{100}{365} = 27.3\%. \tag{6.13}$$

6.2.3 ET dependent sleep interval

As mentioned in 6.2.2 the aim is to have the sensor nodes adjust their sleep timers according to the weather, i.e. prolong the periodicity of the system during rain but keep the number of samplings constant (lower the frequency).

This solution however, is constructed under the assumption that ET_0 (and thereby the crop specific ET_C) is constant, resulting in the simplification of Equation (6.5) into Equation (6.6). In other words, ET_0 is calculated once, used as input and then never recalculated. This approach does not account for time dependent variations of ET_0 and as a result the periodicity (T) of the system is also considered static during non-rainy days.

This translates to the linear relationship described in Figure 6.4, between θ (which depends on ET_0) and time. This relationship however, is quite misleading as the differences between calculating ET_0 based on mean yearly, seasonally, monthly, weekly, daily or hourly values differ greatly. In areas where substantial changes in wind speed, dewpoint or cloudiness occur during the day, hourly calculations of ET_0 are recommended [13]. This because such weather changes can cause the daily average to misrepresent the evaporative power of the area and thereby introduce errors into the calculations.

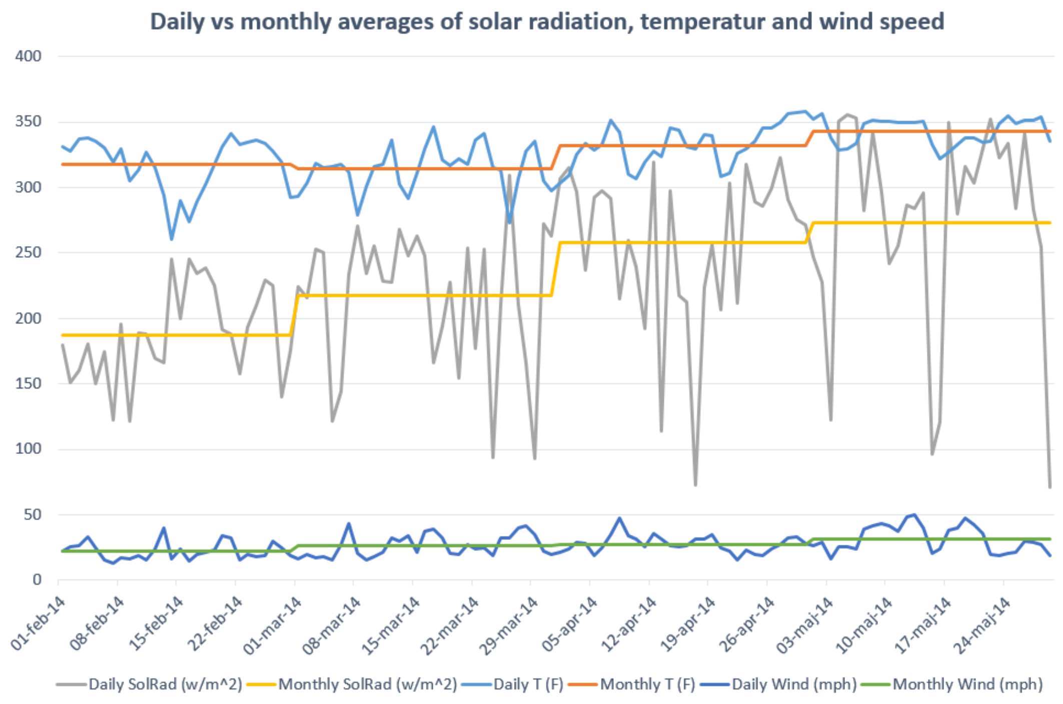


Figure 6.5: How the daily mean values for solar radiation, temperature and wind speed in Fort Lauderdale, Florida, compare to the monthly averages. http://fawn.ifas.ufl.edu/data/reports/

As an illustration of these weather changes see Figure 6.5, in which it becomes clear how much the daily climatic data sometimes stray from the monthly average. Particularly the daily solar radiation values stray from the monthly average. But even the daily temperature average can differ quite a lot from the monthly average. These discrepancies lead to the conclusion that the daily ET_0 value also differs somewhat from the monthly average. This relationship is presented in Figure 6.6.

As presented in Figure 6.6 the daily ET values can differ greatly from the monthly average and particularly from the yearly. This implies that there are possible gains in power consumption to be made by lengthening the periodicity of the system even on non-rainy days.

However, which time step to use for the ET_0 calculations depends on the purpose of the calculation, the accuracy required and the time step of the climatic data available. ET_0 is, as mentioned in 2.1, calculated with the help of climatic data. This implies that, in order to shorten the ET-calculation interval, that same data needs to be available for such short intervals. Thankfully today, with the advancement in meteorology, automation and electronics, leading to an increasing number of automated weather stations, such data is increasingly reported hourly or with even shorter intervals. This hourly data together with automated ET calculations in irrigation systems, allows the Penman-Monteith equation to be re-calculated hourly, with good results. [13]

Since the aim of this master thesis system is to, among others, prolong the network lifetime, there is definitely motivation for computing ET on an hourly basis. Particularly since the main

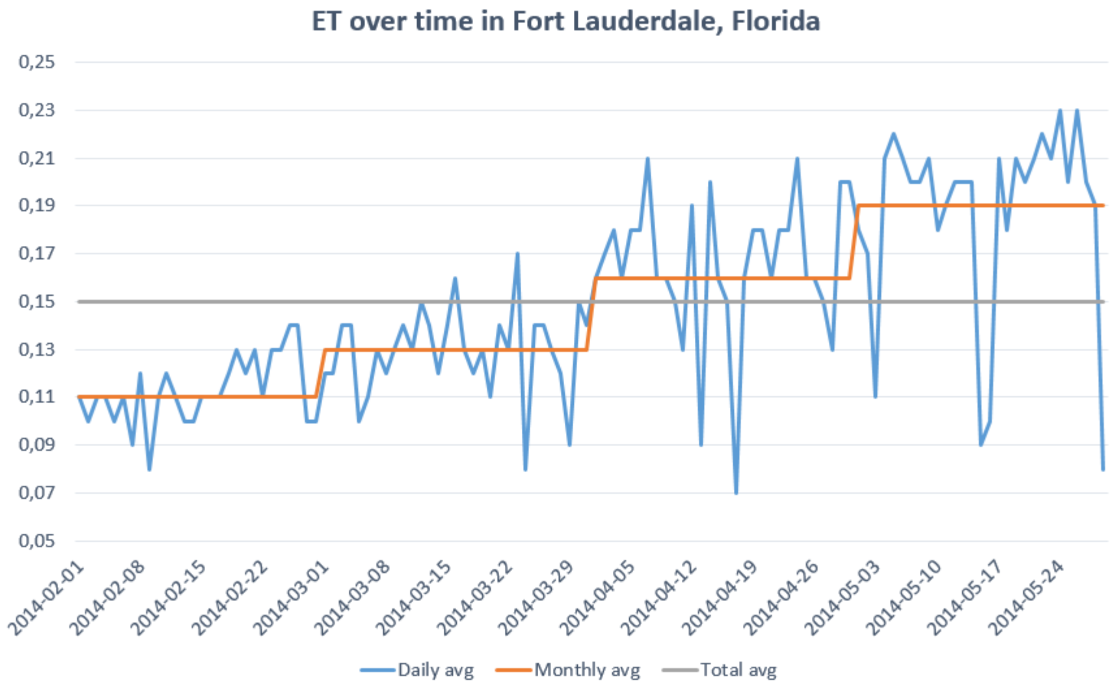


Figure 6.6: How the daily mean ET value fluctuates over time compared to the monthly mean value. http://fawn.ifas.ufl.edu/data/reports/

frame making these computations is under no power constraint.

However, once that data is readily available the question becomes: how often to update the sleep interval of the nodes? This in turn is heavily dependent on the transition costs mentioned in 6.2. If the main frame makes hourly ET calculations and once every 24 hours calculate an historical average for the last 24 hours it would be beneficial if the system could treat that info much like it treats the information of imminent precipitation, i.e. prolong the periodicity of the system since less water than expected has evaporated from the soil.

The cost for a sensor node to wake up from a low power mode and receive instructions from the main frame can be described as:

$$E_{dynamicET} = E_{transition} + E_{RX} \tag{6.14}$$

In other words, the cost for the transition to active state and back to idle state, plus the cost of receiving the instructions from the mainframe.

And in order for this to be worth it, the nodes have to save more power while in sleep mode for the prolonged interval than it costs for them to transition and receive the instructions:

$$E_{transition} < E_{saved} \tag{6.15}$$

$$P_{transition} \cdot t_{transition} + E_{RX} \cdot k \leq E_{saved} \tag{6.16}$$

7 Results

In this chapter the resulting proof-of-concept system and the internal information flow will be presented.

7.1 Physical system overview

The final physical system, upon which all software have been tested and developed, consists of two sensor nodes, one resistive moisture sensor and one sink node connected to a standard PC running Ubuntu through a VirtualBox installation, see Figure 7.1. The arrows back to the node indicate the two-way communication that was implemented to enable dynamically changing sleep intervals.

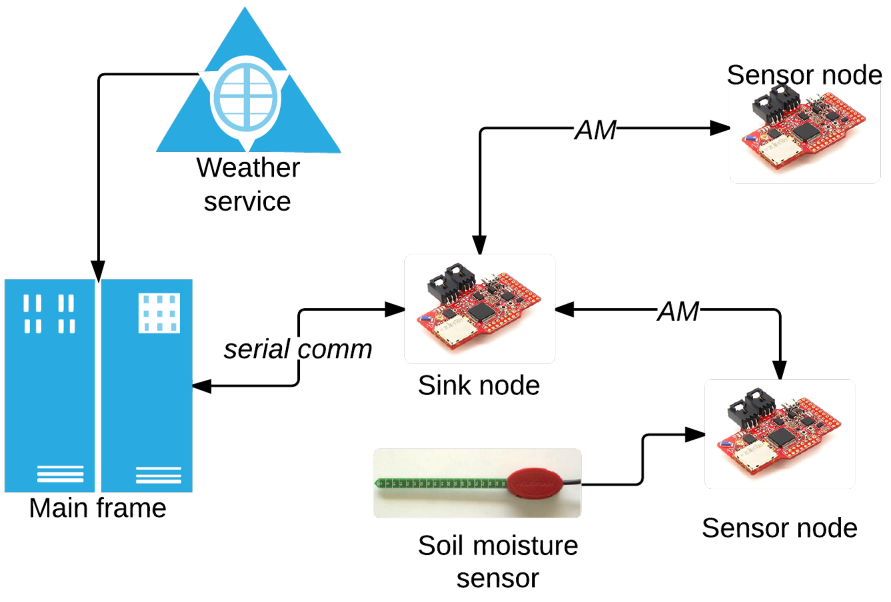


Figure 7.1: The final system with two-way communication implemented.

7.1.1 Node functionality

Apart from the functionality implemented in Section 5, to fulfil the performance discussed in Section 6.2, the system needed to be able to:

- Have two-way communication between the sensor node and back-end system.
- Dynamically change the sleep interval of the sensor node.

The two-way communication was simply implemented by letting the radio listen to incoming messages for a set amount of time. The node started an alarm as soon as the sleep timer had fired, which enabled listening after the node had sent the sensor data.

The sleep intervals where updated by adjusting the periodic timer to the new value, as seen in Algorithm 1.

```
if Message Received then
    if NewSleepInterval != OldSleepInterval then
        Update Periodic Timer with NewSleepInterval;
    end
end
```

Algorithm 1: Outline for updating the sleep interval for the node.

7.1.2 Back-end functionality

The back-end system performed the task of calculating the new sleep interval for the sensor nodes, and the new functionality can be observed in Figure 7.2 (the red text). The querying of the database and calculations for the sleep interval was done in a Java program. As soon as a node sent sensor values to the sink node which forwarded the sensor data to the back-end system, this Java program sent back the sleep interval right after the needed calculations were done. This to prevent the node for spending unnecessary time listening for a response.

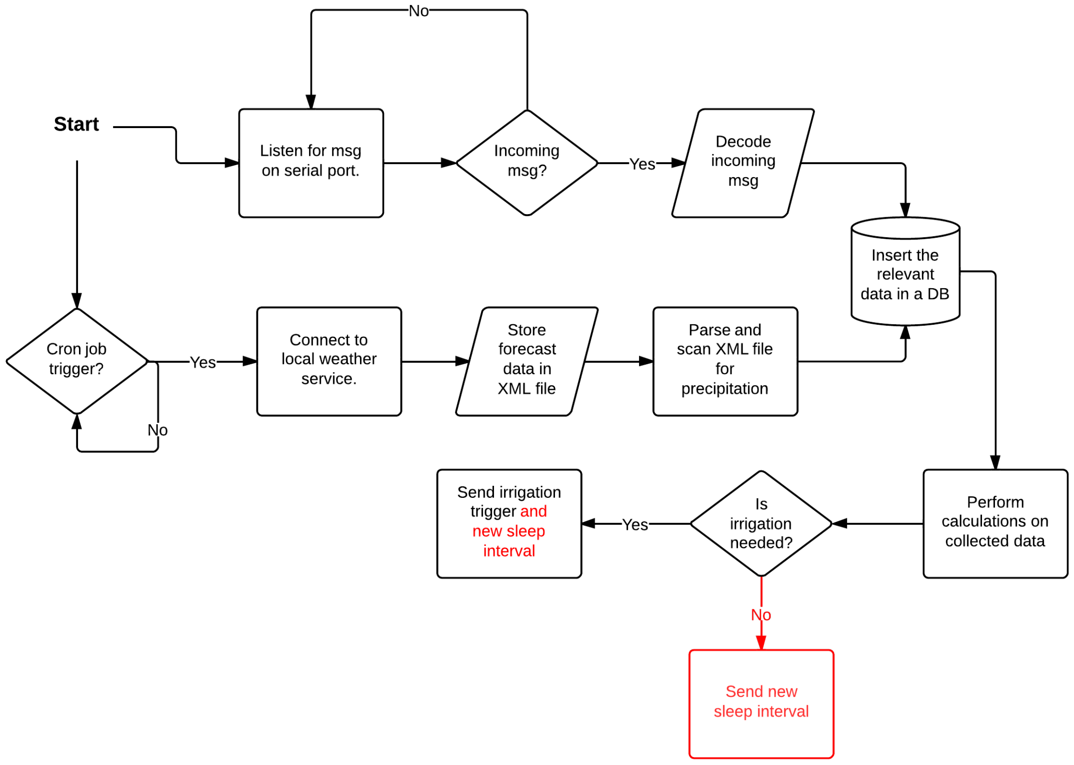

Start
Listen for msg on serial port.
Incoming msg?
No
Yes
Decode incoming msg
Insert the relevant data in a DB
Cron job trigger?
Yes
No
Connect to local weather service.
Store forecast data in XML file
Parse and scan XML file for precipitation
Perform calculations on collected data
Is irrigation needed?
Yes
Send irrigation trigger and new sleep interval
No
Send new sleep interval

Figure 7.2: A flowchart of back-end code that calculates new sleep intervals for the node.

7.2 Node life span

Since power optimization is of great importance to WSNs, as discussed in Section 3.3.2 and 3.3.6, it was also important to try and estimate the power consumption of the proof-of-concept system in order to get an indication of the network and node lifespan. Therefore, an estimation for the chosen set-up (see Section 2.2.7) was made with the help of the following equation:

$$E_{node} = \sum_i U_i I_i T_i, \tag{7.1}$$

where T_i is the time each component i is active, I_i the nominal current consumption and U_i the voltage level required by i. The time T_i is calculated in the following way:

$$T_i = \frac{CPU_{cycles}}{CPU_{speed}}, \tag{7.2}$$

where CPU_{cycles} is the number of CPU cycles, or ticks, the component is active when the speed is CPU_{speed} in Hertz [99, p. 68]. To estimate the battery life span, a few assumptions were made:

Assumptions:

- The batteries used are 2 Energizer Ultra+ AA Lithium batteries with a nominal voltage of $1.5V$ each [100, 101].
- The battery voltage never drops below a pre-set cut-off level and can supply the same amount of current regardless of current load state. [100, 101].
- The current does not ramp up, i.e. transient current behaviour is disregarded.
- Sensor data sampling is conducted every 15 minutes.
- The radio is sending at its maximum signal strength ($0dB$).
- The radio sends the message only once.
- The sensor is turned off when it isn't used, i.e. it does not draw current in between measurements.
- No packets from the main frame are received since the updated sleep intervals will be sent seldom enough to be disregarded in this estimation, see Section 6.2.

The energy consumed in the node during one period is presented in Table I below.

Table I: Current consumption for a Z1 node during period $T = 15min$ [27, 67, 102].

Component	$I_{nominal}$ (A)	T_{active} (s)	$P_{est.}$ (J)
MSP430			
Active@1MHz	0.5 mA	427.2 ms	0.64 mJ
LPM3	0.6 μA	899.57 s	1.62 mJ
CC2420			
OFF	<1 μA	899.57 s	2.7 mJ
RX	18.8 mA	0 s	
IDLE	426 μA	3.53 ms	2.32 μJ
TX@0dB	17.4 mA	5.94 ms	0.31 mJ
VH400			
Active	7 mA	418 ms	8.77 mJ
SUM			14 mJ

How much energy a battery can deliver is highly dependent on the cut-off voltage allowed, i.e. how much to original voltage level is allowed to drop during use before the circuit starts malfunctioning [101]. The chosen batteries can supply 33 mAh hours if the cut-off point is 1.5 V and 1879 mAh if it's 1.4 V (the radio stops working at 2.6 V). This results in two very different scenarios for life span presented in Table II.

Table II: Two different lifespan scenarios depending on cut-off voltage for the chosen batteries.

Data	**Scenario 1**	**Scenario 2**
Battery energy	33 mAh	1879 mAh
	51 mWh	2742 mWh
	183.6 J	9871 J
P_{node}	56 mJ/hour	56 mJ/hour
Lifespan	136 days	669 days
	4.5 months	22 months
	0.37 years	1.83 years

As shown in Table II the lifespan differ greatly with only 0.1 V difference in cut-off voltage. This is further discussed in Section 8.1.1.

7.3 Fulfilment of requirements

Requirements

1. The sensor nodes *shall*
   1.1. be deterministically deployed.
   1.2. be able to read the soil moisture level.
   1.3. utilize two-way communication with the main frame.
   1.4. turn off redundant circuits when in idle mode.
   1.5. cost < € 120
   1.6. have a life span of at least 6 months.
2. The soil moisture sensor *shall*
   2.1. have a speed of measurement < 5 seconds.
   2.2. stay within 5% margin of error.
   2.3. cost < $ 100
3. The network *shall*
   3.1. be self-healing.
   3.2. utilize the 6LoWPAN protocol.
   3.3. minimize communication overhead in the transport layer.
   3.4. be scalable (1-100 nodes).
   3.5. be able to handle movable nodes (neighbour discovery).

4. The back-end system *shall*
    - 4.1. collect and store weather data from a local weather service going back at least 1 week.
    - 4.2. store data from the sensor nodes going back at least 1 week.
    - 4.3. make decisions regarding irrigation based on collected data.
    - 4.4. depending on weather/sensor data decide on sleep intervals for the nodes.

Table III: Fulfilment of requirements.

Requirements	**Fulfilled**	**Comment**
1.1	✓	
1.2	✓	
1.3	✓	
1.4	✓	
1.5	✓	
2.1	✓	According to specifications.
2.2		Sensor has yet to be implemented.
2.3	✓	
3.1		TinyRPL couldn't be implemented due to HW issues.
3.2		See above.
3.3	✓	AMsend utilizes UDP instead of TCP/IP.
3.4	✓	Yes, although TinyRPL would've been better.
3.5	✓	Movable: yes. Neighbour discovery: no.
3.6		
4.1	✓	
4.2	✓	
4.3	✓	
4.4	✓	Yes, this is done once a day.

8 Discussion

In this chapter the results of the background study, proof-of-concept system and analysis will be discussed. The different choices and approaches will be evaluated and the foundation for the future work chapter will be laid out.

8.1 Requirements revisited

As shown in 7.3 Fulfilment of requirements not all requirements were fulfilled and this is due to a number of different reasons. In this section the most important factors in the success and failure of these requirements will be discussed.

8.1.1 The sensor nodes shall

All requirements except *"1.6 have a lifespan of at least 6 months"* are considered fulfilled. Requirement 1.6 will thereby be discussed in this section.

The battery life span calculations in Section 7.2 *Node life span* are not very reliable. As shown in Table II the lifespan of the node differs between 0.3 years and 1.8 years with only 0.1 V difference in cut-off voltage and since no communication overhead is considered, see Section 8.1.3, and no network simulations have been carried out it's unlikely that the estimated life span is accurate.

Furthermore, the currents used to calculate the power consumption for the node circuits are nominal currents specified in the components data sheet and have not been verified.

The estimated lifespan range, $0.3-1.8$ years, is hard to correlate to other real life deployments. In the LOFAR-agro project [9] nodes only lasted 3 weeks on 2 AA-batteries and in [7] the backbone nodes lasted 6 weeks (on 42 Ah batteries) whereas the leaf nodes seemed to be able to last the shelf life of the batteries. Shelf life is the time an inactive battery can be stored before it becomes unusable, usually considered as having only 80% of its initial capacity, for many battery brands this corresponds to approx 10 years [103].

The longest expected life time for similar products on the market today, see Section 3.2.1, is 6 months running on AA batteries.

Furthermore, according to [100], the used approach to calculate the battery lifespan is expected to give inaccurate results, as one has to take the battery's non-linear behaviour into account to acquire a correct battery life estimation. To achieve a more realistic approximation of the battery life time, one could equip the nodes with real batteries and analyse the discharge. However, since the node draws very little power it was uncertain whether the voltage level would have had time to drop enough to provide an accurate reading of voltage drop and the experiment was therefore not conducted.

Instead of using the nominal currents specified in the components data sheets, one could, like the authors of [104], utilize an oscilloscope to analyse the current consumption. This however requires an advanced setup between the nodes and the oscilloscope that could switch between milli-ampere (start-up phase) and micro-ampere (sleep phase). The company was not able to provide the hardware needed, and KTH did not have equipment good enough to be able to sample the 1 MHz CPU frequency.

Finally, even if the life span calculations don't deliver useful information, one important observation can be made. The soil moisture sensor consumes approximately 8.77 mJ in comparison to the 14 mJ consumed during an entire sampling cycle. This means that the sensor consumes $8.77/14 = 62.6\%$ of the total energy, which is a majority. This was not part of the hypothesis, and means that the choice of sensor and how often to sample is an even more important aspect than previously anticipated.

8.1.2 The soil moisture sensor shall

It was a difficulty finding soil moisture sensors online that were good enough for the requirements stated in Section 4.1. After a quick inquiry, one can reach the conclusion that the companies supplying soil moisture sensors that aren't of the type *Electrical Conductivity Probe*, have developed the sensors with the intention that they should be incorporated into a fully working solution provided by these companies [53, 51, 40, 48, 37]. This meant that it was difficult to order sensors online, as the companies rarely supplied any information on how the sensors could be implemented to another source than the one they provided.

A requirement that weren't mentioned but in retrospect should have been a part of the demands on the sensor were the input voltage. The reviewed sensors [92, 94] which were supplied by DC voltage, had the lowest voltage operating level at 3.3V. As the battery solution integrated with the Z1 node were built for two AA batteries, which supplies a total of 3V, the problem were obvious. This meant that the node could only get stable output when plugged into a PC with an USB port, which removed the whole point of the wireless network demand. The implementation did however utilize the V_{CC} +3V output, which gave stable enough output to demonstrate the solution. However, the problem with using the V_{CC} output is that the sensor will utilize power even though the MCU isn't sampling. A solution would be to utilize one of the GPIO pins on the node as output by setting one of the pins output to 1, wait for the 400ms the sensor needs to stabilize output, sample and then set the pin to 0. As the 3 V output wouldn't be enough for a good implementation anyhow, this weren't done. In retrospect, this might have been a faulty decision as turning on and off the sensor only when it was necessary were an important design choice feature needed to make the proof-of-concept system demonstrate the power saving aspect. Also, the existence of this feature were assumed when calculating the battery life span. This assumption was motivated by the fact it would be a very ill-advised move to not turn a component off when it isn't used, and would an important next step to improve the proof-of-concept system.

Apart from the hardware issues, there were one problem with the software implementation that could be improved. As mentioned in Section 6.2, the sampling interval used in most systems (and in the implemented one) were assumed to be correct, or more precisely, often enough not to miss important changes in the system. The difference between sources focusing on irrigation and precise agriculture also give an indication that this field have not been studied enough. As every sampling is expensive energy-wise, it is important to mention this aspect even though the participants in this project did not have the knowledge to do the evaluation needed.

8.1.3 The network shall

The reason why not all network requirements were fulfilled is the fact that no 6LoWPAN protocol was implemented on the proof of concept system. Instead direct transmission through AMsend is used, see Chapter 5, despite the fact that the Analysis states that the preferred implementation is cluster-based routing over 6LoWPAN (see Section 6.1). The reason for this is unfortunately hardware related. TinyRPL is implemented on two basic example programs named *PPPRouter* and *UDPEcho*. PPPRouter is the program that should be running on the sink node (root), it provides the basic setup needed to forward data to and from the main computer frame. This is were problem arises. The Z1 node have 8kB of RAM, and as BLIP (the uIP stack) takes up a lot of memory, PPPRouter (which utilizes 9.2kB) cannot be implemented. This means, to avoid problems, that the best solution is to implement the program on different hardware, which has been a recurring problem throughout the thesis. The solution of building a border router from scratch is not preferred, as it is the implementation of the BLIP stack itself that limits the memory usage, not the implementation.

It's mentioned in the online TinyOS documentation that efforts have been made to shrink the RAM usage of the *PPPRouter* program. However, those changes have not been committed to the TinyOS trunk. The Ubuntu version (12.04) used in the master thesis utilizes an older version (4.5.3) of the compiler needed to compile TinyOS programs, namely gcc-msp430 4.6.3. The only significant difference between the versions is the code size, gcc-msp430 4.6.3 supposedly decreases the code size with 10-12% making the PPProuter shrink to approximately 8,096 kB.

However, gcc-msp430 4.6.3 isn't supported by Ubuntu 12.04 Precise Pangolin why Ubuntu 14.04 Trusty Tahr was installed (it natively supports it). This would've fixed it, had it not been for the fact that the computers used in the thesis couldn't handle the excess process power needed for the upgrade from 12.04 to 14.04. The 12.04 is the last version of Ubuntu which utilizes Unity 2D, after 12.04 all versions come with the new Unity 3D which, on systems without decent OpenGL support, will run by using LLVMPipe, which will come at the cost of higher CPU usage.

Had there been more time when this issue was discovered the issue could've maybe been resolved but as none of us are very comfortable in Ubuntu environments it was concluded that it would take too much time to try to solve it without knowing if it could really be solved. Therefore, TinyRPL isn't implemented in the current proof-of-concept system. For a complete run-down of software and hardware issues, see Section 8.3.

In Section 6.1.1 it is concluded that MOECS probably would outperform TinyRPL, even when utilizing a 127 byte packet size. However, in this preliminary analysis the overhead cost of control messages needed to set up and maintain the different routing paths are not at all taken into consideration. In TinyRPL a trickle timer decides at which intervals control messages should be sent once the initial tree is set up. This trickle timer increases exponentially with each successful transmission leading to, in a stable environment, potentially very low overhead [105]. TinyRPL also attempts to self-heal locally before generating a complete reset of the DODAG. In MOECS however, where the role of CH is rotated for load balancing purposes, new clusters are formed at set intervals generating a constant control message overhead. To calculate the cost of these overhead messages the 1st Order Radio model won't suffice, a proper network simulator is needed. It is therefore not possible to surely claim that MOECS outperforms TinyRPL but the results are interesting enough to motivate further analysis with a proper simulator.

8.1.4 The back-end system shall

All requirements tied to the back-end system have been fulfilled, resulting in a fully functioning back-end system utilizing Django+SQLite as database system, Cron as work scheduler for the weather data download and Java programs for serial port sniffing and sleep interval computing. The choice to use Django and SQLite is more thoroughly discussed in Section 8.3.4 below.

8.2 Outcome of implementation

As mentioned in Section 1.1, 4.1 and 5 the reason for building the proof-of-concept system was to evaluate whether the design choices and the resulting prototype could be used in a real-life deployment. Furthermore it also provided insight into how the different routing protocols were actually implemented as well as knowledge on sensor node hardware and operating systems.

As discussed in Section 8.3 and 8.3.2 the choices made did not result in a prototype ready for deployment, and Section 9 (*Future work*) presents some of the improvements needed for the prototype to reach this goal. The most pressing issue is the choice of hardware, which should be re-done. With that problem fixed most of the other issues mentioned in Section 8.3 and 8.3.2 would resolve themselves, leaving the rather large task of successfully implementing the TinyRPL protocol.

Other than evaluating design decisions, the engineering task of actually building a prototype has provided a lot of valuable insights into product development techniques, scrum project development, open source software and sensor node hardware.

To sum things up, with TelosB/TMote Sky nodes instead of Zolertia Z1 nodes and TinyRPL implemented (or even better, a IPv6 compliant MOECS) the proof-of-concept system isn't necessarily suitable for actual deployment but could definitely be the starting point. TinyOS is used in both [5] and [9] and TMote Sky nodes in [6] and MicaZ nodes in [54].

8.3 Design choices revisited

In the beginning of the Master Thesis the company recommended both hardware and software based on previous, similar but not identical, projects and experiences. Because of this and the fact that the original scope of the thesis was very extensive it was decided to go with the company's recommendations and only conduct a small online survey. Sadly, this led to much grief later in the project when issues arose that neither party could've predicted. In this section the choices made are reviewed and the flaws in the research, leading up to those decisions, pointed out.

8.3.1 The software choice revisited

As mentioned in chapter 4 (Method) the project started out using the Contiki operating system, but the choice was later made to switch to TinyOS. This choice was a result of a number of issues and obstacles with open source operating systems in general and Contiki in particular, namely:

- The documentation on Contiki is, to say the least, lacking. Although the code is written in C (which was a help), almost all code examples lack proper commenting and unless one has a very deep knowledge of the system it takes a lot of time to figure certain things out.

- The choice to communicate with the sink node via the serial port turned out to be the wrong one since Contiki doesn't to support serial port writing/listening in combination with IPv6-radio communication (issues arose when compiling).

- The simulator COOJA only supports the chosen hardware to a certain extent. In fact the only really compatible hardware is the TMote Sky/TelosB mote.

In retrospect the research leading up to the software choice should have been more extensive. But since the company recommended using Contiki, and had good experience using it, assumptions were made that lead to a more shallow research which ultimately hurt the thesis. The issue was discovered rather late in the project (around week 12). The reason it was discovered late was the extensive research into WSN technology that was the main focus the first part of the thesis.

Using the helpful tool Google Trends, it can further be shown why Contiki maybe shouldn't have been the first choice. Google Trends allows one to enter keywords and let Google analyse the frequency and relative interest over time for those search terms. This can be used as an excellent indication on how active the online community related to the search term is, as well as the general popularity of something.

From Google Trends: *"Numbers represent search interest relative to the highest point on the chart. If at most 10% of searches for the given region and time frame were for "pizza," we'd consider this 100. The numbers on the graph reflect how many searches have been done for a particular term, relative to the total number of searches done on Google over time. They don't represent absolute search volume numbers, because the data is normalized and presented on a scale from 0-100. Each point on the graph is divided by the highest point, or 100."* [106].

When comparing TinyOS to Contiki the graph in Figure 8.1 is produced, which shows that the relative popularity and interest over time for TinyOS is, and has been, significantly larger than that of Contiki, although it has been declining since it's release in 2003.

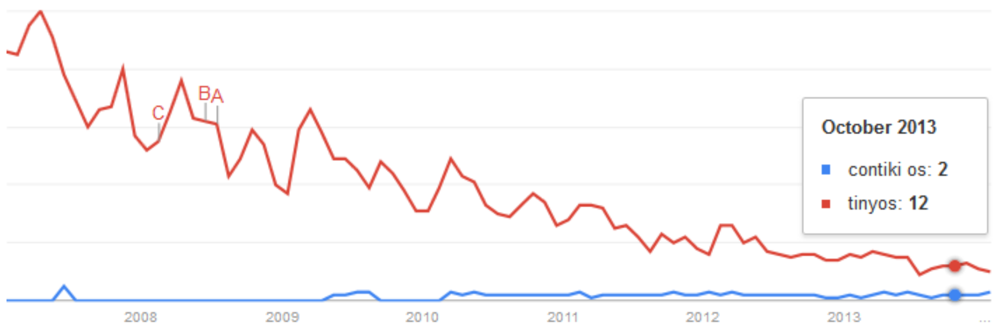


Figure 8.1: Graph of interest over time for the shown search terms.

It's interesting that although the two were released the same year (2003) [83, 84] the interest over time for TinyOS has been significantly larger. This trend can be interpreted as an indication of how active the online community around the two different systems are and since open source always struggles with bad and lacking documentation it is of utmost importance that when running into an issue, there's help to be found.

Furthermore, the original plan was to simulate the behaviour of a large scale network with the help of a simulator. Looking at the two simulators COOJA and TOSSIM, they appear to have the same functionality and since the choice already was leaning towards Contiki, no further research was conducted. However, when once again utilizing Google Trends to analyse the two it becomes obvious that the interest over time of one by far surpasses the other, see Figure 8.2.

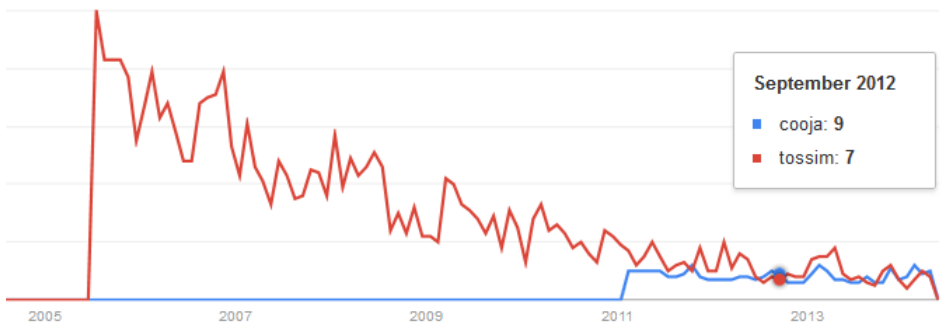


Figure 8.2: Graph of interest over time for the shown search terms.

As seen in Figure 8.2 the interest over time for TOSSIM is far greater than that of COOJA and also stretches further back in time leading to, probably, more active communities, less bugs, more robust software and more supported hardware platforms. However, the gap between the two have been decreasing leading one to believe that COOJA is gaining momentum.

Regardless, with this information it's obvious that TinyOS should have been the original choice of software.

After the switch

In the end, Contiki was chosen because of the anticipated steep learning curve of having to adapt to nesC. Furthermore, the characteristics of the protothreads seemed easier to adapt to and the feature of programming and building applications in a Virtualbox installation of Instant Contiki seemed straight forward. Expertise regarding Contiki was also available at the company, and the OS was used in a previous related project.

However, after having learned that Contiki suffered from issues which were difficult, if not impossible, to overcome without a well-documented source, it was decided to switch to TOSSIM. This solved the, at the time, critical issue of not being able to utilize the serial port in parallel with the IPv6 radio. Learning nesC also proved to be less of an issue than expected thanks to a well documented and thought through API.

However, TOSSIM turned out to be more of a disappointment than COOJA since it has no graphical user interface and only support MicaZ motes, at which point the simulation aspect of the thesis was down prioritized.

8.3.2 The hardware choice revisited

When the lacking hardware support was revealed it led to the notion that the hardware choice also should have been more extensively researched. But again, the scope was considered too large already and the initial online research didn't reveal enough to change the decision. However, out of the 31 Contiki compatible platforms it would've been worth to at least research some of the more popular ones. Which those were was in retrospect determined with Google Trends, see Figure 8.3.

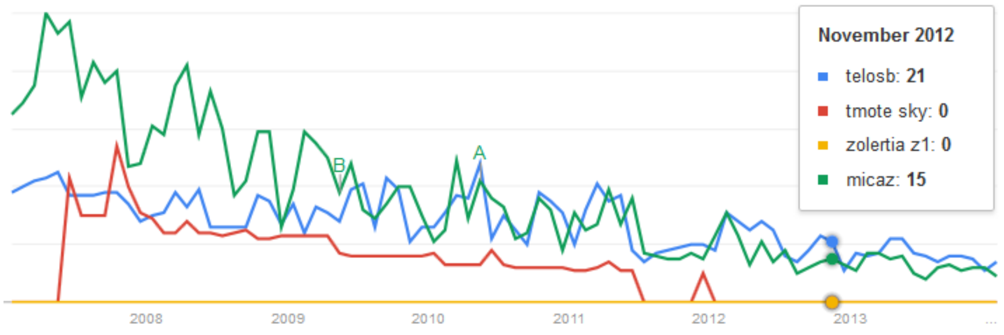


Figure 8.3: Graph of interest over time for the shown search terms.

As can be seen in Figure 8.3 the TelosB/Tmote Sky platform has a longer history of activity/interest online but it has been declining over time. The predecessor of the IRIS mote, the MicaZ, was also very popular a few years ago (IRIS is too new to generate enough traffic to show up in Google Trends). Looking at this information it's obvious why the software has the most support for TMote Sky/TelosB and MicaZ (COOJA and TOSSIM respectively), they've been around the longest and are by far the most popular. Had this been known, the hardware choice would've most definitely been different.

To further compare them a table was put together, see Table I below, in which it's apparent that they differ very little in actual hardware why the research related to popularity and interest over time becomes even more important.

Table I: Characteristics of the TMote Sky, IRIS and Z1 motes [27, 28, 29].

Evaluation criteria	**TMote Sky/TelosB**	**Crossbow IRIS**	**Zolertia Z1**
Processor			
MCU	TI MSP430F1611	Atmel ATmega1281	TI MSP430F2617
VCC	1.8 ... 3.6 V	2.7 ... 3.6 V	2.1 ... 3.6 V
Flash	48 kB	128 kB	92 kB
RAM	10 kB	8 kB	8 kB
ADC	12 bit	10 bit	12 bit
Current draw: Active	0.5 mA @ 1MHz	8 mA @ 4MHz	0.5 mA @ 1MHz
Current draw: Sleep	2.6 uA	8 uA	0.5 uA
RF Transceiver			
Radio chip	TI CC2420	Atmel RF230	TI CC2420
Data rate	250 kbps	250 kbps	250 kbps
Transmission power	0 : −25 dBm	0 : −24 dBm	0 : −25 dBm
TX range outdoors (0 dB)	125 m	> 300 m	180 m (antenna)
Current draw: RX	19.7 mA	16 mA	18.8 mA
Current draw: TX	17.4 mA @ 0dBm	17 mA @ 3dBm	17.4 mA @ 0dBm
Current draw: Sleep	1 uA	1 uA	< 1 uA
Electromechanical			
GPIO	16 pin	51 pin expansion	52 pin
Onboard sensors	3	-	3
Power supply	AA/USB	AA/USB	AA/micro USB
User interface	1 button, 3 LEDs	3 LEDs	1 button, 3 LEDs
Cost	€ 77		€ 95

8.3.3 Simulators

As mentioned in Section 8.3.2 COOJA didn't support the chosen hardware in the way, or to the extent, that was expected. On Contiki's homepage no differentiation is made between the different supported hardware platforms leading one to believe that a further investigation is unnecessary. That however, proved not to be the case.

Almost all code examples in COOJA support the TMote Sky motes but few support the Zolertia Z1. Furthermore, the function 'collect view', which allows real time tracking of battery power, packet loss, packet latency, temperature sensor value and so forth, turned out to only support the TMote Sky. This played a part in the switch to the TinyOS system as it was believed, after some initial research, to be more robust, extensive and that the TOSSIM simulator supported more platforms.

That however, was not the case. In fact, TOSSIM only supports the MicaZ motes when simulating on hardware. Leading the switch to TinyOS to be virtually useless in terms of simulator abilities.

However, when once again utilizing Google Trends to analyse a number of open source network simulators it becomes obvious that perhaps a completely different choice of simulator should have been made, see Figure 8.4.

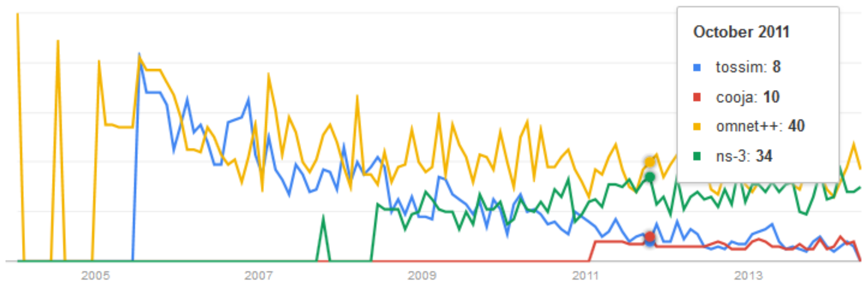


Figure 8.4: Graph of interest over time for the shown search terms.

As seen in Figure 8.4 the interest over time for OMNeT++ and ns-3 is far greater than that of COOJA/TOSSIM and also stretches further back in time leading to, probably, more active communities, less bugs, more robust software and more supported hardware platforms. However, the original scope didn't leave much room for learning a completely new simulator program, instead the aim was to use COOJA/TOSSIM to simply verify that the actual written code could scale as the great benefit of those simulators are that one can compile actual source code and simulate it on nodes in the program. And had only the hardware been different many issues could've been avoided.

8.3.4 Back end

The back end of the system consists of the MVC Django which is written in Python. No actual research was conducted into the area of MVCs as Python was a known language and the proposed options in PHP and Ruby would've required learning a new language. However, looking back, very few of the Django's functionalities are actually utilized leading to the conclusion that maybe another MVC could've done the job better? An initial online survey of internet forums revealed CodeIgniter (PHP) and Ruby on Rails (Ruby) as the biggest contenders. Again, Google Trends was used to analyse the interest over time for the different frameworks, see Figure 8.5.

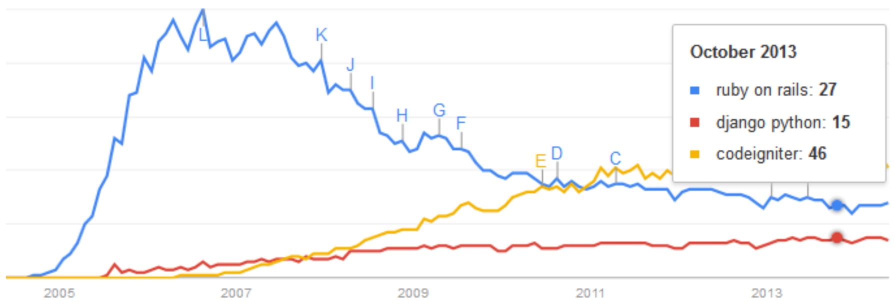


Figure 8.5: Interest over time for Django (Python), CodeIgniter (PHP) and Ruby on Rails (Ruby).

The graph in Figure 8.5 clearly shows that, at least historically, Ruby on Rails had the most active online community and highest interest. But lately PHP based CodeIgniter and Django have been gaining momentum leading to the conclusion that the choice of Django probably didn't influence the thesis in a negative way. Rather, time was saved by choosing an already familiar language (Python).

8.4 The hypotheses revisited

As outlined in Section 1.3 (*Hypothesis*) a couple of hypotheses were developed during the background study to be used as guidelines during the master thesis. This section will briefly summarize the findings related to each hypothesis as well as make references to the relevant paragraphs in the thesis.

- *A suitable setup for an irrigation system consists of sensor nodes, soil moisture sensors, one sink node and a main frame functioning as back-end.*

  Yes, as presented in Section 2.2 (*Characteristics of WSN*) and 3.2 (*WSN in precision agriculture*) most existing WSN deployment aimed at irrigation utilize soil moisture sensors, some kind of grid pattern for the sensor nodes, one (or more depending on size) sink nodes and a back-end of some sort.

- *Weather data can be used to lower power consumption.*

  Yes. As shown in Section 6.2 (*Dynamic sleep intervals*) utilizing weather to determine sleep intervals could indeed lower the power consumption of the network.

- *A feedback system could improve the performance of the system.*

  As no actual deployment was carried out there is no way of definitely knowing whether the proposed feedback solution will indeed improve the performance. However, as discussed in Section 4.2 (*System control loop*) and 6.2 (*Dynamic sleep intervals*).

- *The routing scheme can be self-healing and robust without drawing too much power.*

  Yes and no. There is no easy answer to this question as shown in Section 3.3.3 (*Robustness*), 6.1 (*Network design*) and 6.1.1 (*TinyRPL vs MOECS*) since each installation, depending on use, size and purpose will have to weigh the pros and cons of a, somewhat, energy costly robust network against the pros and cons of a less power consuming and less robust system. But the results in 6.1.1 (*TinyRPL vs MOECS*) are promising when it comes to power consumption of a self-healing and self-organizing robust network.

- *The most important design decisions related to power management are power mode handling and network setup.*

  Yes and no. It's been discussed in both Section 3.3.2 and 3.3.6 that these two are pivotal when managing the power dissipation of the system but what can be an even bigger culprit is the sensors, as discussed in Section 6.2 and 8.1.1.

After revisiting the hypotheses, the conclusion is that a lot of knowledge has been gained on how to design a WSN-based smart irrigation system. However, as mentioned in 1.4 (*Scope*), what's also become evident is how much more knowledge, outside of the embedded software domain, that is needed for a successful deployment.

The challenge lies in designing a well-functioning routing protocol while keeping energy cost from peripheral components, like the sensor, down to a minimum. There are still some work to be done before the prototype can be tested in a real-life deployment and those possible improvements are presented in Chapter 9.

9 Future work

In this chapter the future work related to the discussed topics in Section 6 (*Analysis*) and 8 (*Discussion*) will be presented.

9.1 Hardware

In this section the different future solutions for hardware will be presented. All recommendations for future work are based on the discussions in Section 8.1.2 and 8.3.2.

9.1.1 Nodes

As mentioned in 8.3.2 the original choice of the Zolertia Z1 node proved to be less than ideal. This was mainly due to the issues mentioned in 8.1.3, namely that the RAM memory was too small for the TinyRPL-programs but also that the hardware not being supported fully by the simulators. Furthermore, the analysis in 8.3.2 clearly shows how other hardware platforms outperform the Zolertia Z1 in terms of interest over time and thereby active online community.

As a result, the future work regarding hardware would be to switch to the TelosB/Tmote Sky platform, since it's fully compatible with the software and simulators, have more RAM storage and a larger online community.

9.1.2 Sensors

The switch to the TelosB/Tmote Sky platform does however not solve the issue with the soil moisture sensor mentioned in Section 8.1.2. It still needs a voltage supply of 3.3V or 5V to run properly, which requires an external battery powered circuit solely for the sensor or that the entire sensor be replaced.

The future work here consists of finding a better suited sensor (which can run on 3V) or to construct an external circuit.

The other problem mentioned in Section 8.1.1 were the use of a sampling interval that was estimated according to different sources. Work conducted to finding an optimal sampling interval would therefore improve the system, and is also suggested as future work.

As the availability of sensors online were limited, another approach and future work would be to develop a soil moisture sensor with low power consumption suitable for the application.

9.2 Software

In this section the different future solutions for software will be presented. All recommendations for future work are based on the discussions in Section 8.1.3 and 8.3.1.

9.2.1 Operating system on nodes

As mentioned in both 4.3.1 and 8.3.1 the issues with the chosen software are tightly linked to the chosen hardware. If the hardware is disregarded there have been no major issues with neither Contiki nor TinyOS, besides the bug in Contiki which made it impossible to utilize the serial port while simultaneously listening to radio messages.

Furthermore, the initial analysis regarding routing protocols suggest that a IPv6 compliant routing protocol would outperform RPL. Therefore an implementation of an IPV6 compliant cluster-based routing protocol would be a preferable future work.

On the same note, the data aggregation algorithm is still not very refined in this thesis can could definitely be improved for better performance over all.

9.2.2 Simulator software

Another quite necessary aspect of the future work concerns the simulators. Both COOJA and TOSSIM, with the right hardware, could probably deliver satisfactory results if enough time were given. However, OMNET++ is regarded as one of the best network simulators and probably therefore a good choice for evaluating routing metrics. So, in short, the future work consists of:

- If TinyOS: Keep the serial approach but if IPv6 is the goal then there's no point in utilizing the serial port, then everything should go via a web server.
- Implement a IPv6 compliant cluster based routing protocol.
- Utilize a proper network simulator to verify initial results regarding routing.

9.2.3 Back-end

As mentioned in the Method section 4.4.1, the chosen database implementation SQLite have shortcomings not suitable for a bigger deployment than the one conducted in this project. The choice were mainly made on the fact that neither of the project participants had any previous knowledge on how to handle and implement databases. SQLite have the advantage of being easy to setup and therefore a good alternative for inexperienced users. To ensure scalability and features like users and permission management, future work would be to implement a better suited database. After a quick screening by utilizing the Google Trends tool and consulting with the company, a good choice of replacement for SQLite would probably be MySQL, see Figure 9.1.

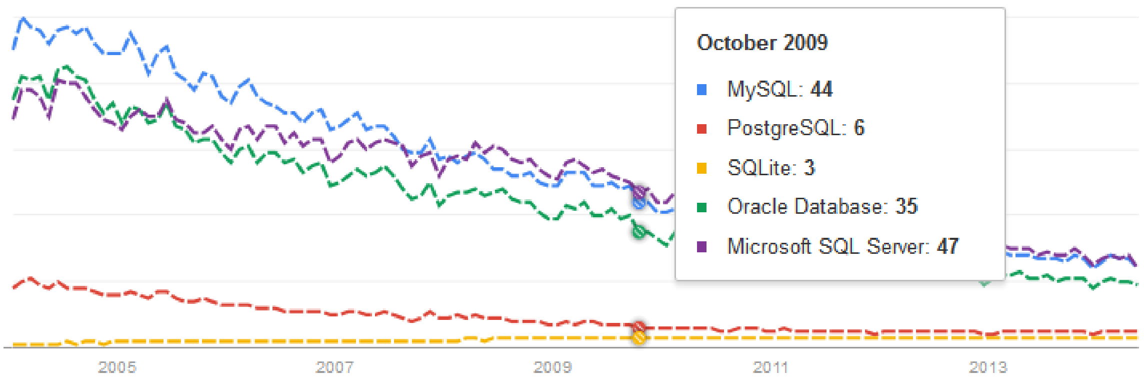


Figure 9.1: Graph of interest over time for the shown search terms.

9.2.4 Front-end

As mentioned in Section 1.4 (*Scope*), implementing any kind of user interface was outside the scope, as it wasn't needed to perform the task. However, the advantage with having a front-end system is the possibility to easy evaluate the data that is stored which could improve the over-all performance. Therefore a possible future work would be to develop some kind of front-end system with the possibility to analyse the stored data.

9.3 Implementation of physical test-bed

As been mentioned throughout the whole project, as the field of study being Mechatronics, a real-life implementation have not been possible. However, if the discussed design choices should be tested thoroughly, they need to be tested in a real life deployment. This would mean a collaboration together with ethnographers, biologist, irrigation hardware specialists etc. Many of the difficulties with handling electronic solutions in agriculture are directly dependent on the fact that the environment is hostile. Many of the assumptions and design choices might be invalid if knowledge for the actual deployment environment is disregarded.

If a real-life deployment were to be implemented, it would probably result in a similar setup as in [6, 7, 5, 9, 55], with a deployment of approximately the same amount of nodes as in the test-bed chosen in Section 6.1. However, a lot of work to be conducted before this set-up could be possible, even after the issues brought up in Section 8.1 have been cleared.

Some of the benefits of doing this kind of deployment are mentioned in the bullet list below:

- Evaluate if sensors other than the soil moisture one should benefit the system.
- Finding out what kind of features the nodes need to ensure robustness outside.
- The actual battery life of the nodes could be studied.
- Study the actual packet-loss that are due to outer factors.

9.4 Verification

As mentioned in Section 8.1.1, the technique used to estimate the battery life span was not accurate enough. Future work would here be to build a current measuring setup good enough to accurately measure the small currents on the sensor nodes, along with a simulation environment to test the results [104].

10 Conclusion

The system design choices of a smart networked irrigation system is a balancing act between the available energy of the network sensors and the acceptable maximum packet loss ratio (robustness). To be able to achieve a satisfying end-product, adapting the choices to the implementation is of utmost importance. The design choices discussed and evaluated in this master thesis include:

- Hardware choices: Choosing hardware with a low power consumption is essential if the system is going to have a long life span. Deciding on a power-efficient and reliable sensor is especially important as the sensor is the component which consumes the most energy. 8.3
- Network: How the network is designed is one of the most important design decisions, and includes several sub-categories including; network topology, routing protocol, data aggregation scheme and so on. Choosing an appropriate network will greatly affect how well the system is performing. 6.1

To take advantage of both sensors and online weather data services, a feedback control loop is proposed to gain precision on water dispersed, and with that increasing crop yield and saving water. With this proposed feedback-loop a solution to dynamically change the sleep interval is introduced. By changing how long the sensor nodes are turned off in proportion to how much precipitation is expected, the nodes can save up to 30 +% of the available energy . Furthermore an improved solution, also proposed in this master thesis, is to dynamically change the sleep intervals according to how ET fluctuates over the course of 24 hours or perhaps a week, instead of keeping ET static for long periods of time. 6.2

Smart irrigation systems are meant to be deployed in agricultural contexts, and every area of deployment have unique characteristics which can differ greatly from each other. Therefore it is important to take the unique on-site variations into consideration while designing the system to acquire the optimal performance of said system. To further analyze the results acquired in this thesis, a real-life deployment analysing network behaviour and life span would greatly increase the understanding of said system. The knowledge gained could be used to improved the system even further. 9

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A Scope issues

Appendix to review the initial conditions of the project and the iterations made to reach the current problem definition and scope.

A.1 Initial problem definition

Initially, the foundation for this project were created by Daniel Thysell at Sigma Technology. He had a vision for a project that focused on an engineering task which was summarized as:

- *Mesh radio network for measuring moist level in plantation and combining that with online weather service to provide input to a pump system.*
- *Network to be controlled, managed and used by web-based user interface.*
- *Classic Internet of Things-application.*

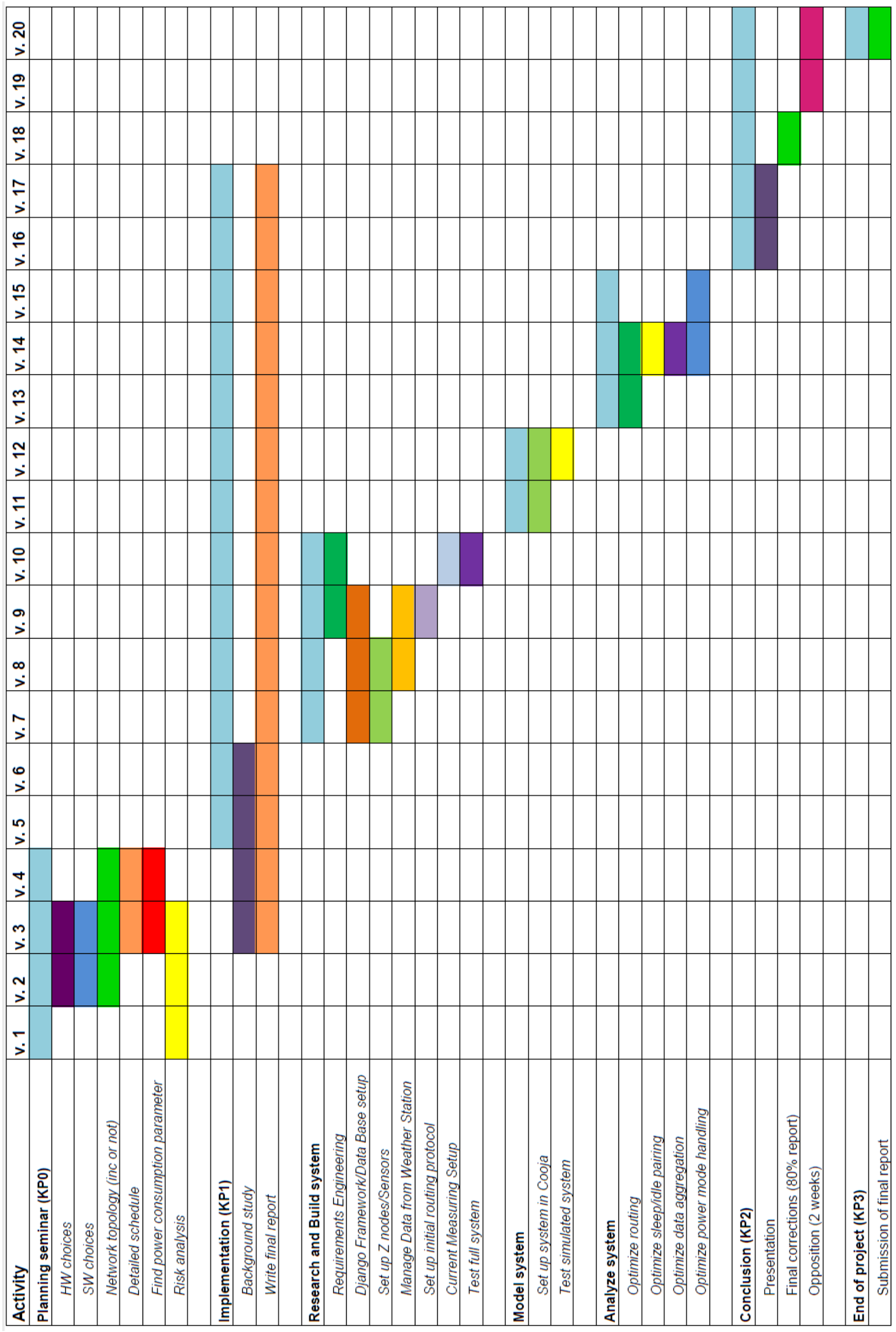
However, as KTH expected a project which contained a scientific evaluation and the presented one only contained an engineering task, the project were re-evaluated. Together with KTH and the company the scope changed to focus on the power consumption aspect of the intended physical system. The finalized problem definition were decided as:

"Can the over-all power consumption of the wireless sensor network be lowered with the help of power-efficient algorithms and network optimization based on the chosen implementation? The chosen implementation being an autonomous irrigation system deployed over a large area (requires a scalable system) with a significant amount of nodes, all connected to one central database. The system output is a water distribution system (i.e a pump), and the system input will be collected from moisture sensors and a local online weather service."

To answer the research question, the chosen methodology consisted of a few steps. Firstly, after conducting a background study, the parameters which affect the total power consumption of the system were to be identified. These parameters were to become the foundation of the working hypothesis for the rest of thesis. When these had been identified, the task were to evaluate how (and if) these parameters could be tweaked/manipulated in order to decrease the over-all power consumption. To achieve this, the project were intended to do two different engineering tasks.

Firstly, a prototype would be built of the defined system, with two sensor (Z_1) nodes communicating with a main computer frame through a border router. This means that the first method used would be a controlled experimental environment, where the nodes, sensors and main computer frame will be included. Secondly, in order to verify the behaviour of the prototype, and ensure scalability, the system would also be simulated with a significantly larger amount of nodes in the software Cooja. The use of a simulation environment were intended as a complement to the limitations of a controlled experiment, and ensure that the network communication would be tested thoroughly.

The time frame were set at 20 weeks and were intended to follow the time planning presented in Figure A.1.



Activity	v. 1	v. 2	v. 3	v. 4	v. 5	v. 6	v. 7	v. 8	v. 9	v. 10	v. 11	v. 12	v. 13	v. 14	v. 15	v. 16	v. 17	v. 18	v. 19	v. 20
Planning seminar (KP0)	🟦	🟦	🟦	🟦																
HW choices		🟪	🟪																	
SW choices		🟦	🟦																	
Network topology (inc or not)		🟩	🟩	🟩																
Detailed schedule			🟧	🟧																
Find power consumption parameter			🟥	🟥																
Risk analysis	🟨	🟨	🟨																	
Implementation (KP1)					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
Background study			🟪	🟪	🟪	🟪														
Write final report			🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
Research and Build system							🟦	🟦	🟦	🟦										
Requirements Engineering									🟩	🟩										
Django Framework/Data Base setup							🟧	🟧	🟧											
Set up Z nodes/Sensors							🟩	🟩												
Manage Data from Weather Station								🟨	🟨											
Set up initial routing protocol									🟪											
Current Measuring Setup										🟦										
Test full system										🟪										
Model system											🟦	🟦								
Set up system in Cooja											🟩	🟩								
Test simulated system												🟨								
Analyze system													🟦	🟦	🟦					
Optimize routing													🟩	🟩						
Optimize sleep/idle pairing														🟨						
Optimize data aggregation														🟪						
Optimize power mode handling														🟦	🟦					
Conclusion (KP2)																🟦	🟦	🟦	🟦	🟦
Presentation																🟪	🟪			
Final corrections (80% report)																		🟩		
Opposition (2 weeks)																			🟥	🟥
End of project (KP3)																				🟦
Submission of final report																				🟩

Figure A.1: A detailed Gantt Chart containing the schedule of the entire project.

The intended plan corresponded well to the working pace, a thoroughly conducted background study were made. However, half-way into the project, several problems started to emerge.

Firstly, to power optimize the intended system, one needs to have knowledge in several areas. Apart from knowing how power optimization works for networks and on node level, extensive knowledge of the implemented system has to be obtained. The realisation gained was that it was probably best to have a complete system to analyse, and not to analyse something that wasn't implemented from the start. This meant that the anticipated workload were far more great than previously assumed.

Secondly, problems with the intended simulation environment emerged. The simulation software COOJA did not support the used hardware in the ways presumed when the project started. This meant that the second part of the engineering task were not possible to implement, and with that a major part of the testing, validation and verification fell short.

Apart from these two problems, more difficulties arose when the understanding of what the problem definition actually promised increased. For example, a lot of the power consumed by the nodes corresponds to the chosen network implementation. Therefore, implementing a well-chosen routing protocol matching a suitable test-bed is the best approach to ensure power optimization. However, implementing a functioning power-optimized routing protocol is not an easy task, and would require both a lot of time and knowledge of the hardware, software and algorithms that the participants of the project did not have.

Also, a part of the project were to evaluate where the power savings corresponding improvements on node level could be made. However, most of the State Of the Art knowledge of this kind of power saving techniques are already implemented on the operating systems designed to be used on sensor nodes. This meant the improvements made would probably be neither noticeable nor implementable. Also, if an actual improvement were implemented on the system, one would have to be able to validate the power consumption on the node by utilizing some kind of way to measure current. As the nodes current levels are very tiny in size (micro Ampere) an advanced setup had to be used, and that would require knowledge, resources and time not available.

All these problems were enabled due to assumptions made in the beginning of the project without any real knowledge backing the assumptions up. The problem definition promised far more than was realistic for two mechatronic students to conduct during a 20 week period. In short, the scope was way too big.

A.2 Scope change

When the problems that had arisen in Section A.1 were analysed, the conclusion reached was that the scope was way too big. The only way to finish the master thesis within the time frame of 20 weeks was to reformulate the research question and with that the scope. The goal was to make sure that the work conducted so far in this process hadn't all been in vain. However, to reach many of the conclusions made in Section A.1, an extensive research had been conducted to the few relevant subjects. A gap in the market were discovered along the way, together with the motivation on why an autonomous WSN based irrigation system was interesting in the first place. The revised plan was therefore to focus on the system design choices and to build a proof-of-concept system for the company to evaluate if the design choices were implementable.

The power optimizing angle did not go to waste either, as an important aspect of all WSNs are the limited power supply. The findings made on the subject were incorporated when making the design choices. However, as the power optimization no longer were the sole purpose of the thesis, all of the validation and verification previously discussed were no longer necessary. The network part of the thesis became more of an evaluation of the different possibilities suited for both the chosen test bed and the implementation corresponding to the gap in the market. With this new problem definition, the knowledge gained and research conducted so far did not go to waste, and the important findings along the way could be presented and not neglected by the scope.

A.3 Cause for scope issues

So what was the cause of the scope issues? There can be several wrongdoings identifiable when analysing the initial process of this project. Most of them were done by making assumptions without backing them up with knowledge on the subject. For example, the initial project presented by the company were probably well suited in the aspect workload versus disposable time. By having to evaluate the power consumption of the system as well as building the it made the scope too big. However, if the project were to evaluate the power consumption of an existing system with a finished hardware and software setup, paired with an already working simulation environment, the magnitude of the scope would probably be more well-suited for the intended 20 weeks. By building the system and trying to set up the testing environment as well as conducting the actual tests, the estimated time to finish everything would probably be a lot more than 20 weeks.

This mistake has its source in several causes. The biggest is, of course, the knowledge of the participants of the project. The assumption made that the scope were suitable according to the time frame was done on the premises that the all planned tasks would execute smoothly. The eagerness to start the actual project probably only increased the problems, making the project start before the problem description were thoroughly revised. An evaluation of the knowledge of the participants, a more thorough risk analysis and consulting the knowledgeable people involved probably would have increased the chances of not making the mistakes mentioned.