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Master of Science Thesis in Embedded Systems

Multihop Transmission for Time Correlation in Energy Harvesting Networks

Gerrit Maurice Willemsen

Embedded Networked Systems

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Embedded and Networked Systems Group
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology
Mekelweg 4, 2628 CD Delft, The Netherlands

Gerrit Maurice Willemsen
g.m.willemsen@student.tudelft.nl
mauricewillemsen@live.nl
TU Delft Student Number: 4366662

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Author
Gerrit Maurice Willemsen (g.m.willemsen@student.tudelft.nl)
(mauricewillemsen@live.nl)
(**TU Delft Student Number:** 4366662)
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Graduation Committee

dr. Rango Rao Venkatesha Prasad (direct supervisor)	Delft University of Technology
dr. ir. Chris Verhoeven	Delft University of Technology
dr. ir. Zaid Al-Ars	Delft University of Technology

Abstract

We consider a system of IoT nodes powered completely by energy harvesting. This work focuses on achieving the time correlation of data measurements in a network of energy harvesting sensor nodes. Time correlation is achieved by hopping a message through the whole network. This message wakes up all the nodes and lets them perform a measurement. Measurement data is added to the transmitted message and is collected by a gateway at the end. The nodes harvest energy from a Radio Frequency (RF) source and store it in a capacitor. When the capacitor has sufficient energy, the nodes can turn on their system. A low power Wake-Up Receiver (WURx) is turned on and the nodes fall asleep while waiting for the incoming request message. Communication is done using active transmissions and the ultra-low-power WURx for data reception. Nodes consume a continuous power of less than 2 μW in sleep mode while the WURx is turned on. The receiving sensitivity is -40 dBm, which limits the communication range. The request message hops through the network to overcome distance limitation. Collisions are avoided with Clear Channel Assessment (CCA) using the WURx. The hidden node problem is overcome by toggling an operational amplifier during CCA. Distance limitation is overcome by a novel network layer algorithm. The network layer algorithm finds a directed acyclic graph (DAG) based on all nodes, starting in a single special source node and ending in a gateway. Data from all the nodes are gathered in a round, where each node can transmit one message around. The timing interval between the data collection is chosen to be bigger than the required energy divided by the minimal harvested power. In this way, all nodes will have sufficient energy in every time interval. The found DAG represents all important links where the nodes should wait for before measuring and transmitting. Other data from previous nodes are added to the transmission of the nodes. In this way, the gateway will receive data from all nodes with the minimal time difference between their measurements. Simulations show that a correct gateway oriented DAG solution is always found for random networks. In > 92 % of the cases, all nodes are taken into account in this solution and in 6% of the cases, just one node is missing. Nodes have been designed and evaluated. We can power the nodes with a minimal RF input of -15 dBm. The receiving range is found to be 8 m from a 10 dBm On-Off Keying (OOK) transmission. With 6 μW harvested energy, data from all the nodes can be gathered every 15 minutes.

Preface

This thesis is the final result of my master “Embedded Systems”, and concludes my years of studying at the TU Delft.
The past year has been a challenging, but interesting experience. I learned a lot about radio waves, energy harvesting techniques and low power system implementations. Yet, i gained the most knowledge about doing research and tackling a project of this size. It has been tough to come up with a novel research contribution and to implement the proposed solution on a real system was a challenging task. Nevertheless, I am glad with the achieved results. Noticing the solution working on devices without batteries or any power wires, was satisfying.

I would like to thank my supervisors, Sujay Narayana and Dr. Rango Rao Venkatesha Prasad, for their guidance during the project, for giving me the opportunity to come up with a research problem, and for letting me implement my solution as a real test system.
Furthermore, I would like to thank my friends, family and above all, my girlfriend for their support during my years of studying, and especially during this year of my master thesis.

Gerrit Maurice Willemsen

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Chapter 1

Introduction

There are many sources of energy around us, such as sunlight (solar energy), vibration (mechanical energy) and radio waves (electromagnetic energy) [39]. When sufficient energy can be harvested from these sources and efficiently converted to electric energy, low power electronic sensor nodes can be powered from them. Techniques for harvesting energy exist for a longer time, but it was not prevalent. However, the recent development in CMOS technology gave rise to improved harvesting techniques and decreased power consumption in sensor nodes [39]. This made it possible to power sensor nodes by sources from the ambient. Nowadays the interest in this technique has grown a lot by the increased interest in small sensor nodes that are placed all around us. These sensor nodes are used to sense environmental parameters, and the gathered data can be used to take necessary action [18]. With the growth in the number of these nodes, the interest in self-sustainable energy in these nodes has increased as well. Having sensor nodes without batteries and mains power gives advantages in terms of product costs, product size, maintenance costs and harm to the environment due to batteries.

Multiple sensor nodes can increase the reliability in data collection. When deployed to cover certain space they can provide additional information about their surroundings such as spatial variations in the surroundings. When harvested power is limited, the nodes need to duty cycle their active states [47]. This means they harvest energy for a while, shortly turn on, and then measure and transmit their data. This limits the times they can report their data to the amount of energy they harvest. A Random collection of the data measurement between different nodes results in measurements both different in time as well as in space. This work focuses on correlating data measurements of multiple sensor nodes in time over an area or a particular system.

To showcase where this time correlation is needed, the following use cases outline the problem:

- By having multiple sensors placed in a pipeline, measuring pressure, the data can expose a leakage or a blockage in the pipeline. In smart agriculture, this can identify the blockage which may lead to crops getting dried or prevent a leakage which helps us save water, which is scarce and costly.

The time correlation is necessary as the total pressure can be constant over time causing different measurements over time to have a different reference measurement. To compare values properly, it is necessary to compare them at the same reference measurement point in time. The sensors can be powered, for example, by the vibration of the fluid, by the radio waves from a nearby FM, TV or GSM tower or by tiny solar cells.

- Another example where leakage can be detected is thermal leakage. Sensors can be placed in the hull of an aeroplane to measure the temperature. If there is a thermal leakage temperature will drop a little and deviating values can be measured by the sensors around it. Time correlation gives an equal reference for the temperature in the hull. Besides temperature, pressure in the hull or the air-controlling systems of the aeroplane can be measured and undesirable leakage costs can be decreased by performing directed maintenance.

1.1 Challenges

Nowadays, solar cells are the most commonly used environmental energy source. Depending on their size, they can provide a broad range of power from μW for single nodes to kW for providing energy to buildings [39]. This work considers energy sources with limited available power thereby considering tiny solar cells, vibration harvesters and radio-frequency (RF) harvesters. The challenges are summarized as follows:

- An important challenge is to harvest the small available amount of power and store it for later use. The harvested energy is predominantly used for wireless transmission to report the measured data. In theory, sufficient energy can be harvested for data transmission when the node is turned off for long enough. However, polling an active radio for data reception to respond to other transmissions is not possible with these power levels.

- To achieve time correlation, the nodes in the network need to know when to take measurements. Time information can be achieved by a clock to keep track of time. However, a clock would consume significant energy of the energy budget and would require receiving synchronization messages to prevent clocks from drifting. If the node can receive messages, a request for an immediate measurement lets the node know when to perform the measurement. Time correlation can be achieved by requesting all nodes at the same time. Hereby, the challenge, on the one hand, is to reduce power consumption while waiting for a message and on the other hand to make sure receiving nodes are turned on and have sufficient energy when requests occur.

- With a network of nodes that are limited by energy to transmit only once in a period and that need to multihop messages, a network algorithm should make sure that a gateway can collect the data from all nodes without the need for nodes to transmit twice.

The overall challenge is to find a low power solution that ensures collecting data from all nodes with a limited time difference.

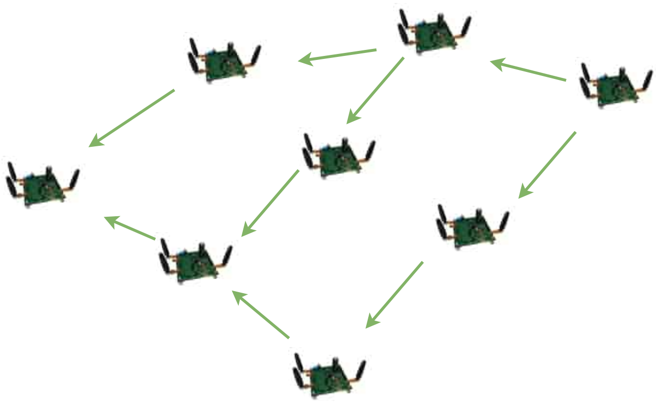


Figure 1.1: **Network overview of proposed solution. The green arrows form the important incoming links where other nodes wait for.**

1.2 Research Questions

This work aims to find a hardware and network solution for a network of multiple EH nodes to achieve time correlation. The goal for the nodes is to report their data once in a time interval with a short time difference between the measurements of the nodes. To limit power consumption and to be able to support nodes that harvest minimal power, the study focuses on letting all nodes transmit once within the time interval. A hardware solution is required that harvests energy from the ambient source and one that can be informed to take a measurement when it is required. The method should make sure that all nodes are turned on at the same time. A network algorithm is required for the nodes to report their data to a gateway with the limitation that they can transmit once in a time interval. The research question is as follows:

How can data be gathered periodically at the same time in a network of energy harvesting nodes while power is limited and nodes can only transmit once in a defined time interval?

1.3 Proposed Solution

The proposed solution, in this work, achieves time correlation between data measurements, is a novel algorithm that collects data from all the nodes in a network by waking them up and letting them perform a measurement. Waking up is done by hopping a message through all nodes in the network. The message collects data from all nodes and reaches the gateway. The hardware implementation of a node has an RF energy harvester to power the nodes. Nodes harvest energy and wake up when they have sufficient energy. When a node is started, it waits for an incoming request message. The node has an ultra-low power wake up the receiver (WURx) to receive messages from its neighbours. By harvesting the power from an On-Off Keying (OOK) data transmission itself and reading out the data pattern in this signal, data is received. This receiver consumes 1 μW, but is limited in sensitivity to -40 dBm. Total power consumption is 2 μW when the node is asleep while the WURx is on. Nodes retain sufficient energy while waiting for an incoming message if their the harvested power is >2 μW. Data is gathered in rounds which are started in a special source node, and through multiple hops, over other nodes, it reaches the gateway which collects all the data. The hopping is to overcome the distance limitation due to the limited sensitivity in the WURx. When the time interval between two collection intervals is bigger than the time it takes for the least harvesting node to harvest sufficient energy, all nodes are expected to be awake. The hopping message takes all data from nodes on its path. A novel algorithm is proposed to let data hop by all nodes. This algorithm ensures that all nodes know their primary important links from that of sidepaths where they should wait for, to take all data measurements to the gateway. This is shown in Figure 1.1 where all green arrows demonstrate important links between the nodes. All nodes transmit only once in a data collection round and therefore collisions are expensive. Collisions are avoided with performing a clear channel assessment before transmitting. To overcome the problem of not sensing a hidden node, an operational amplifier is shortly turned on during clear channel assessment.

1.4 Contribution of Thesis work

The work done in this thesis provides a novel approach to the transmission of data in a network of EH powered nodes. Contributions are summarized as follows:

- A novel algorithm that is proposed; it finds a Directed Acyclic Graph (DAG) from one end of the network to the other end. This DAG represents the links in the network that ensures that data of all the nodes can reach the gateway by a single transmission of each node in a time interval. By letting a message hop over all paths in this graph and collect the data of all nodes, time correlation between data measurements is achieved.
- The collision avoidance mechanism by toggling an operational amplifier to prevent hidden nodes, to the best of our knowledge, is a novel contribution.
- The RF energy harvester and WURx are comparable to the state of the art.
- This thesis contributes to scientific research by showing that it is possible to create multihop networks and achieving time correlation between data measurements in networks of EH powered nodes that harvest a minimal amount of continuous power. This is not only done by simulating but by demonstrating a real implementation as well.

1.5 Organisation of the Thesis

The work in this thesis is divided into different sub-parts where each chapter considers a part of the implementation. The communication of the system is divided into different layers according to the OSI Model [11].

- Chapter 2 describes the background theory of the different subjects in this work and discusses the results achieved in the state of the art related works.
- Chapter 3 outlines some global system topologies and presents the chosen solution. The overview of the implemented hardware is given as well.
- Chapter 4 describes the design of the energy harvesting part that harvests RF energy and describes the energy modelling of the nodes.
- Chapter 5 describes the design of the low power WURx that is used to receive data.
- Chapter 6 describes the collision avoidance mechanism which is used to get reliable communication between different nodes.
- Chapter 7 describes the proposed network layer algorithm that finds a directed acyclic graph of the network that ensures collecting all data.
- Chapter 8 describes the test results of the overall test containing all individual parts of the system.
- Chapter 9 outlines the conclusions based on the work done for this thesis and answers the main question.
- Chapter 10 describes the future work that could improve the work done in this thesis.

Chapter 2

Background Theory and Related Work

This chapter describes the background theory that is needed to answer the research question. The first half considers energy harvesting theory and related studies. The second part outlines the low power techniques used in the communication layers.

2.1 Energy Harvesting

Energy harvesting is an old technique which has become more interesting in the last decade as devices consume less power due to evolving techniques. In energy harvesting the energy from a source is transformed to electrical energy. Available power is usually less than the needed power to perform a command and therefore this energy is stored. This leads to intermittent devices having a duty cycle between an ON state, consuming more energy than the harvester provides, and an OFF or SLEEP state, consuming less energy than the harvester provides. Devices operating exclusively from the EH source are never able to consume more energy than is provided over time. Hence the possibilities of EH powered nodes are limited by the energy that is harvested.

2.1.1 Overview of Energy Sources

The maximum potential of energy harvesting is given by the available energy from the sources around the node. The energy in most sources is non-electrical and has to be transformed towards electrical energy to power the system. This will lead to conversion losses. A lot of research is done in finding and measuring potential EH-sources. [39] talks already about possibilities for harvesting energy from sources around us, and the potential energy of the discussed sources is given. In [43] an overview of potential sources and related technique are discussed. [7] discusses different energy sources for health monitoring applications. Light is usually considered as most potential energy source and a lot of research has been done in this field. Challenges lay in vibration, thermal and radio waves harvesting techniques as usually less energy is available.

2.1.2 RF Energy Harvesting

This work aims to find a low power solution that works with these limited available power sources. In this work, RF energy harvesting will be researched further and will be applied to the sensor nodes. Energy in RF waves is harvested using an antenna which produces an alternating voltage over its terminals. The alternating voltage needs to be rectified for the system to use it which will lead to energy losses. First, the available energy in RF waves is discussed followed by the technique to harvest it. At last, the related work with their achieved results is discussed. A broad survey on RF energy harvesting is given by [23].

RF Transmission Power

The RF sources for providing energy can be divided into dedicated and ambient energy sources. Dedicated RF transmitters give controlability for the users, but have power limitations due to RF regulations. With ambient RF energy harvesting, no transmitter is needed. Ambient RF energy harvesting is done from sources that are allowed to have a higher output power. Harvesting from ambient RF is less controllable since a user cannot control the power or signals that are emitted from the source. Devices still need to be in a certain range of the transmitter because of the decay of RF power. The locations of the transmitters are uncontrollable, but they can be found in official regulations. Power density S at a distance d from a transmitter can be calculated according to Friis equations [3] given in (2.1). It appears that the power has a quadratic decay over distance. In (2.2) the effective area of the receiver is given. Combining both equations give the available power at distance d. This is shown in (2.3).

$$S = P_{EIRP}/4\pi d^2 \tag{2.1}$$

$$Ae = \frac{\lambda_{RF}^2}{4\pi} \cdot G_R \tag{2.2}$$

$$P = S \cdot A_e = P_{EIRP} \cdot G_R \cdot (\frac{\lambda_{RF}}{4\pi d})^2 \tag{2.3}$$

The following options increase harvested power:

- Increase Antenna Gain (area, topology)
- Increase Transmit Power
- Decrease Frequency
- Decrease Distance
- *Increase Harvester Efficiency*

With ambient RF Harvesting, there is no control over transmitted power and frequency. If another source with the same transmit power would be available at a lower frequency, this increases achieved power. However, lower frequency has the disadvantage that is needs a bigger antenna. Distance to source can usually not be changed if the node is required at a specific place. Therefore the only thing that can be done to increase RF harvested power, is to increase the antenna size. Increasing the harvester efficiency is a key factor in the further development of RF harvesting systems, but is still limited by the available power in RF signal if all could be harvested.

Source	Frequency	ERP	0 dB isotropic antenna	6 dB directed antenna
FM-Radio	88-102 MHz	80 dBm	13 km	26 km
DVB-T	470-790 MHz	73 dBm	1.2 km	2.4 km
DAB+	174-230 MHz	69 dBm	1.8 km	3.7 km
GSM900	880-960 MHz	63 dBm	190 m	380 m
Custom 3 W	915 MHz	34 dBm	8 m	16 m
Custom 1 W	433 MHz	30 dBm	9 m	19 m

Table 2.1: **Potential distances for given RF sources with two types of receiving antennas.**

RF Sources

Every source that transmits wireless data is transmitting energy in the air. However with the rapid decay of energy in the air, only high power sources are sufficient to deliver enough energy for long distances. Potential high power sources for ambient RF energy harvesting are Analog Radio (FM), Digital Radio (DAB+), Analog TV, Digital Television(DVB-T) and Mobile Broadband (UMTS,GSM,LTE). Besides, certain radiobeacons transmit high power signals as well. All these sources have different transmission power and center frequency. For mobile broadband the transmitted power depends on user data and therefore the amount of users in the surrounding. Where most sources have a limited amount of stations separated far from each other, harvesting in the mobile broadband source is different. Power transmission is less constant and depends on user demands. With high density of users, cell towers in urban area are placed closer together and harvesting can be done from multiple providers, multiple towers or even from mobile phones (although they transmit less power). When users are closer to the station, the station transmits at lower power. Further, a high amount of users will increase transmitted power. Transmitting data to users is done separately from other transmissions with time division (TDD) and frequency division (FDD). The energy can be harvested over the whole time and band. Considering a minimum working power input of -15 dBm, the distances given in Table 2.1 could theoretically be achieved with two types of receiver side antennas. It is noted that the different ERP depends on the transmitter type but that common values are used. In [42], the available energy of different RF sources is measured on several locations in London.

Antenna Characteristics

The type of antenna determines how much energy can be captured. A theoretical isotropic antenna captures energy equally from all directions and therefore has a gain of 0 dB. Practical antennas have more directed gain and there directivity gain is expressed in terms of gain over an isotropic antenna: dBi. A typical half-wave dipole antenna has a gain of 2.15 dBi and a radiation resistance, or characteristic impedance, of 73 Ω. In dipole antennas, the energy is captured with respect to two poles giving an balanced output. The quarter-wave monopole antenna leaves out one of the poles of the half-wave dipole antenna and captures the energy on one pole with respect to a proper ground plane. This antenna radiates only above this ground plane and therefore has twice the gain of a half-wave dipole with half the radiation resistance. Most monopole antenna designs are however matched to 50 Ω to make a standard in the RF world. For the antenna gain it is noted that this maximum gained is achieved if the antenna is correctly directed. Power sources usually have antennas with directivity gain in the horizontal direction. For mobile cell towers, most common setup is to have 3 antennas covering a 120 ° width view. Their gain is concentrated in a horizontal plane giving a value of 18 dBi. The produced voltage on the antenna is given by (2.4) and indicates that a higher resistance gives a higher voltage. Monopole antenna design is often chosen in both radio transceivers and energy harvesters because of the higher gain, compacter design, and it's unbalanced nature. Unbalanced output of the system is needed to feed further circuitry. A BalUn (Balanced/Unbalanced converter) design would be needed to unbalance the output of a dipole antenna but this gives additional losses. However, when monopole antenna design is used, a good ground plane is important for the signal to have a ground reference as the ground antenna pole is omitted. In energy harvesting it is important to capture enough energy out of the air with the antenna. Therefore, directed antennas which are pointed towards the transmitter, are used as they give higher gain. An antenna pole approaches an effective antenna area, but in energy harvesting, flat surfaces are often used to capture more energy while paying attention that it captures around the right frequency. Dual band surface antennas like [2] aim to capture more energy over different frequency bands.

$$V_{amplitude} = 2\sqrt{2R_S P_{AV}} \tag{2.4}$$

Rectification

The rectifier is needed to generate a DC voltage from the input AC waves. Simplest topology would be to use a single diode in series with the antenna. This topology is called a rectenna and is often used as Envelope Detector for measuring the received signal strength. With a charge pump setup of multiple diodes, output voltage can be increased. This is useful in further processing. However, diodes come with a voltage drop which is the biggest energy loss in the harvesting circuit. For low energy input signals, a charge pump of multiple stages increases open voltage but decreases energy efficiency. To decrease the voltage drop to the minimum, schottky Diodes are used which have a small voltage drop. Low Power Shottky Diodes designed for RF are the most suitable because they have their efficiency peak at lower voltages leading to less wasted energy. Review of charge pumps technologies is given in [4]. Despite comparing it to the older short range PowerCast chip, the paper in [33] clearly distinguishes the need for a low amount of multiplication stages. In [35] it is shown that maximum power transfer is achieved for a single stage voltage doubler by matching the input impedance to the output impedance by a factor of 5.3.

Matching Circuit

The matching circuit is crucial for a maximum power transfer and matches the impedance from the antenna to the impedance of the rectifier. From circuit theory it is known that maximum power transfer is achieved when:

$$Zsource = Z^*load \tag{2.5}$$

Source impedance is given by the characteristic impedance of the antenna that captures the RF Energy. Section 2.1.2 discusses the characteristic impedance for different antennas. The load impedance is given by the load divided by the multiplication factor of the rectifier. Matching is done using an LC circuit with center frequency at the desired frequency. Different matching techniques are the T, PI and L matching circuits, named to their topology. The L matching circuit is the simplest version with an inductor and a capacitor. However, the difficulty of this circuit is that the Q factor and therefore the bandwidth cannot be chosen freely. The Q factor is the relation between the bandwidth of the matching circuit and its center frequency, as given in (2.6). A higher Q factor means voltage gain and therefore higher efficiency in the rectification, but comes at the cost of a lower bandwidth. Where a lower bandwidth in communication systems is desired for FDD, in EH it reflects energy which could be used. Following could be done to increase voltage for higher efficiency in the rectifier with respect to the same input RF power.

- Increase Antenna Impedance
- Increase Q factor

$$Q = \frac{f_R}{BW} \tag{2.6}$$

Power Management

Power management part needs to boost the DC voltage level at the output of the rectifier and store the harvested energy in a storage capacitor. Power Management Integrated Circuits (PMIC) are complete IC solutions which boost the input power and store it. They can run from harvested power. Usually they have a cold start period. During this cold start period, the capacitor needs to charge to a minimum level, whereafter the boost conversion can power itself more efficient and overall efficiency is increased. It is important to keep the sensor nodes above this point during operation to keep the power harvesting as efficient as possible. Hence, the chosen capacitor size should provide enough energy while cycling between a minimal and maximal voltage level.

Related Work

Regarding the background theory, related work is stated here that indicates current achieved work. Most older research is focused on porting RFID alike systems to greater distances. For far field RF harvesting, technique is quite the same, although different antennas are used. RF sources on distance become limited in available power and reliability, especially when powered from ambient sources. For RFID systems, the power is enough to directly power the system, and because distance to power transmitter is short, communication is done using backscattering technique. Backscatter does not actually transmits power and therefore consumes limited energy. No energy is stored in these RFID systems so no PMIC is needed.

One of first major research to far field RF powering is done in [44]. Intel Research Lab was one of the first to proof far field energy harvesting working and they achieved $60\,\mu$W after rectification of the theoretical available power of $220\,\mu$W using (2.3). Power was harvested at a distance of 4.1 KM from an analog TV broadcast transmitting 960 kW ERP.

Since that research, there has been a lot of papers in the field of RF energy harvesting. Clearly the main goal with energy harvesting is to maximize the amount of harvested energy. Therefore, the best metric to indicate this is to report efficiency with respect to input power. Sensitivity is important as well, since the harvesting circuit is providing energy from this power input level. Besides efficiency and sensitivity, it is important to state the voltage level achieved as CMOS circuitry needs a certain voltage to be able run on. Although DC-DC converters can boost this, they consume energy for boosting and have a minimal operation level. However this should affect energy efficiency as less as possible. Research papers lacking the efficiency and sensitivity they achieved, are missing the major point.

Not many commercial RF harvesting products are available, most common available product is the PowerCast IC which includes rectifier and PMIC. It is centered around the 868 MHz/915 MHz ISM frequency, but can be used to capture energy in the mobile broadband at the 800 MHz and 900 MHz band as well. It is intended to be used with its dedicated transmitter and has most conversion efficiency between -10 dBm to 0 dBm input power. It is stated to work from -11 dBm for efficient conversion. For ambient transmission this minimum level is really limited. Most work done in research is focused around this input power level as higher efficiency is achieved at higher power level. However it is more interesting to achieve higher efficiency at lower input powers to minimize power difference and to decrease the minimal input level.

Papers as [14, 15] can charge a NiMH battery with levels from -25 dBm, but are not considered relevant to this work. Their power management can run from a certain given voltage by the batteries they charge. Those circuitry are great to increase battery life, but harvested energy is to small to run a system on, and cannot be used to run a batteryless system on. In order to know how much power is harvested, overall efficiency is considered important. In [17] work is focused on achieving high voltage to charge a capacitor, giving 800 mV at -20 dBm but with an efficiency of 3 %, resulting in 300 nW power, which is clearly really low.

In [29], an energy harvester for the FM band is described which achieves up to 50 % at -10 dBm and peaks at 5 dBm. In [9] an entire harvester including voltage amplifier is build in CMOS which achieves 30 % efficiency above -20 dBm. This is no complete power management solution but its efficiency is state of the art.

Harvesting form analog TV transmission is promising for distance due to the amount of transmitted power. In [51] they showed that they can charge a capacitor using a DC-DC converter with receiving -15dBm at a distance of 6.5 KM from a Japanese TV broadcast station. In [34], the signal received from digital television was measured for 7 days and it is shown that the signal is constant over time. In [27] a harvester is able to harvest efficient from an input level of -20 dBm and their DC-DC converter works with a minimal input of -15 dBm.

In [42] the received power levels of potential sources as DVB, GSM900, GSM1800 and UMTS are given, measured in London. From these levels they state that GSM is a potential source in urban environments. In [32] [1] [21] [19], [54] and [50] research is done in the field of GSM harvesting and achieved results on harvesting range from 50 m to 250 m distance to GSM transmitter. [32] achieved to power a temperature sensor with a temperature display running at 3 μA at a distance of 220 m from a GSM transmitter. Overview of current research on

DVB and GSM is given in [30].

Related work shows that ambient RF energy harvesting is still limited but it also shows that efficiency is increasing and a low power solution can run on the harvested energy. State of the art papers can achieve +/- 30 % efficiency between -20 dBm and 10 dBm. Dedicated CMOS can have slightly better performances. In related work that considers boost conversion and a power management system, the critical sensitivity is given around -17 dBm to -12 dBm minimal input power that the PMIC can start boosting from with 10 %-20 % efficiency. With -18 dBm minimal working input power and 10 % conversion efficiency, 1.5μW is harvested. Even if the minimal input power is lowered, the amount of harvested power is extreme low.

2.2 Data Communication within EH Sensors

One of the main challenges in energy harvesting powered nodes is to reduce the energy consumption in the wireless communication. Wireless Communication has a significant energy consumption with respect to harvested power. As stated in Section 2.1.2, transmission power is reduced to a quarter of its original power with doubling the distance. Therefore, to reach a feasible distance, transmissions need to have significant power. Continuous power consumption in the receiving part of the system has to be minimized. This section describes the theory behind low power communication technique and related work.

2.2.1 Communication Protocol Stack

The data communication in a network contains different tasks. Different protocols fulfill these tasks. An abstract way to describe them is by stacking different protocols onto each other. Hereby one protocol can assume the other levels of protocols below them will fulfill their tasks. The most common methodology for this is given in the OSI layering model [11]. This work divides the different tasks within the communication of the system according to the OSI layer model.

2.2.2 Wide Area Networks

Placing sensor nodes within a Low Power Wide Area Network (LP-WAN) would eliminate the need for a self exploited gateway and would give a wide communication coverage. However, communication over the corresponding distance consumes a lot of energy. In [5] an energy model is given for a sensor node based on LoRa communication, energy use is varying with different settings between 1.5 mJ and more than 100 mJ during one interval. ICs implementing LoRa technique have a current consumption of minimal 90 mA @ 2 V while transmitting. Energy difference is due to spreading factor and transmission power. Within LoraWan, messages can be received by the node after its transmission during a certain amount of time. This gives the ability to receive acknowledgements. LoraWan is the network layer above the LoRa physical and link layer. Another LP-WAN technique achieving high communication distance is SigFox. Due to message repetition and a slow datarate, energy consumption in SigFox is considerably high as well. Other LP-WAN techniques consume even more power, and they are designed for random transmission of data with limited ability of receiving information. LP-WAN protocols are unusable as communication technique for the low power nodes in this work. However, the gateway that is placed in the network to collect all data could make use of a Wide Area Network communication protocol to communicate its collected data towards a database.

2.2.3 Physical Layer Techniques

The physical layer describes the physical transmission and reception of data. This layer forms close relation to the data link layer above it as both layers aim to achieve a correct transmission between two nodes. The chosen technique for transmission determines the amount of energy that is needed for the transmission. However, other layers above the physical layer determine the amount of data to be transmitted and the number of transmissions and are therefore important as well in limiting energy consumption.

Active Radios

Active radios as the CC1101 transceiver, CC1310 SoC or BLE radios consume 10 mA - 30 mA @ 2 V when transmitting and 5 mA - 15 mA @ 2 V when listening. Distance highly determines power in transmission. Sensitivity highly determines power in receiving part. Active radio usually have a sensitivity of -100 dBm thereby still overcoming high distances [48]. However, this consumes significant power, and the low power nodes do not harvest enough power to continuously use it.

Wake Up Radio

Power consumption in radio receivers can be reduced by letting them sleep and wake them up when they need to listen. When the receiving node is close enough to the transmitting node, the power in the RF signal is sufficient to be harvested and will indicate an ongoing transmission. The MCU and the active radio are awakened. With increase in distance between transmitter and receiver, the received power, and therefore rectified voltage from the harvester, are to low to wake the MCU. To be able to receive a reasonable distance, an ultra-low power comparator is used to compare the received voltage to a threshold. The ultra-low power comparator is the only active part in the circuit. The comparator detects the transmission and turns on the radio to read data. Even with the comparator, the low power circuit comes at the cost of a decrease in distance compared to an active receiver. Usually for wake up radios it is given that, with increasing the sensitivity, the power consumption is increased as well. In [24], a sensitivity of -55 dBm, -43 dBm -32 dBm is achieved using 3 different comparators with power consumption of respectively 1276 nW, 400 nW 196 nW. As with the RF energy harvesting, dedicated CMOS can significantly improve efficiency. In [56], a fully passive WUR can detect down to -43 dBm. And in [28], -72 dBm with 8.3 nW power consumption is achieved in fully CMOS. In [13], the authors achieved a wake up range of 90m with a current consumption of 3.5 μA and 20 dBm transmission power.

Data Detection using Wake Up Receiver

The output of the comparator directly follows the transmission and when transmission is done using an On-Off Keying (OOK) pattern, the comparator of the wake up receiver outputs the OOK pattern of the signal. This pattern can be read by a MCU thereby eliminating the use of an active radio. Backscatter reception in RFID systems is done this way. However most research papers with active radios focus the pattern reception only on address selection and start the active radio to perform data reception, mainly to increase bitrate or decrease power in transmission after wake up call. In [26], data output is read completely by the MCU for the communication in a Body Area Network.

Backscatter

A technique that does not require active transmission is called backscatter. This technique makes use of available RF signals. It toggles the impedance on an antenna which results in an altered reflection coefficient of the RF signal. Other nodes can see this alternating signal by detecting the difference in achieved signal strength. This technique is used in RFID systems. Because no node actually needs to transmit power, both transmitting node and receiving node consume a small amount of power. The disadvantage is that the communication distance is even more limited and that another signal should be available. This available signal should be a clear signal with sufficient power. Backscattering on ambient RF has been done but is really limited in distance and topology. In [10] and [22] ambient backscatter is tested and distances are limited to 0.5m. Backscattering technique originates from the RFID field where tags were RF powered, and used backscatter to communicate back. Therefore, networks of multiple of these devices are called tag-to-tag networks. Tag-to-tag networks can overcome the distance limitation of backscattering. Tag-to-tag networks suffer from distance and power limitation. To hop over tags, these tags in between should all be awake. Therefore this comes close to the problem in this work. In [25] a multihop solution is proposed for a tag to tag network enhancing the distance of tags to a gateway. The receiving part is done using the technique stated in previous section and uses a minimal amount of power. However, to increase communication range, they use an operation amplifier (opamp) to amplify the input signal. A tiny solar cell is added to keep the nodes powered for all the time to be able to relay message. Another multihop backscatter solution is presented in [58] to let tags that have no line of sight to the gateway, hop over other nodes.

2.2.4 Link Layer Techniques

The link layer describes the way the device can access the communication medium when they want to transmit. Is describes as well how a transmission is received correctly.

Channel Access

Time Domain Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) both give all nodes their own precoordinated timeslot or frequency band. This is mostly used in circuit switched networks, and introduces a lot of overhead and overkill for WSN when nodes have few packets to transmit. In contention based access, nodes try to access the channel at the moment they have a packet ready to transmit. The simplest form is Aloha which simply transmits when it has a packet to transmit. With random transmission of data and multiple nodes that want to transmit, there is a probability that messages will collide. A common way of knowing that a message is arrived, is that the receiver transmits an acknowledgement back. When the acknowledgement is not received within time, the transmitter can transmit again. However this introduces overhead in transmissions and therefore in energy consumption. Collision Avoidance is the technique that tries to prevent collisions as much as possible. In 802.11 (Wi-Fi) and 802.15.4, Carrier Sense Multiple Access with Collision Avoidance is used (CSMA/CA). This means, multiple nodes can transmit over the same channel whereby collisions are avoided instead of detected. Collision Detection is mostly used in wired communication channels. In wireless transmissions. the radio is in use when a node is transmitting and therefore, collisions are hard to detect. Besides, an additional transmission in wireless transmission is far more costly because of the high energy consumption of wireless transmissions. Collision Avoidance is done by sensing the channel before a node wants to transmit. When the channel is in use, the nodes backoff for a random time. Timing parameters are the same for all the nodes and therefore there is no prioritisation.

Error Detection

Nodes need to know if a message is received incorrect, and therefore error detection is important in communication links. Even if there is no collision, the RF environment can introduce noise and messages can be received incorrectly. Most common error detection is the Cyclic Redundancy Check (CRC) check invented by Wesley Peterson [41]. Both transmitting and receiving nodes perform a check over the transmitted data, and the transmitter includes the outcome of the check at the end of its message. The receiver compares the received and calculated values to each other to see if the message is received correct.

Message Reception

Commercial available link layer protocols are mostly called Medium Access Layers (MAC) and combine both the link layer part and the physical layer. The MAC layers of Bluetooth and 802.15.4 consume less energy than always listening MAC layers as WiFi(802.11). 802.15.4 is the building block for network layers as ZigBee, Z-Wave and 6LowPan. Continuously active listening to messages is not possible in low power solutions, and therefore the listening time needs to be reduced. The technique for this in 802.15.4 is duty cycling the listening time. The transmitter is synchronised to transmit in the right time span, done in 802.15.4 or S-MAC [52]. When time period is short, the transmitter can transmit a long preamble overlapping at least a time period. This is done for instance in B-MAC [16]. With transmitting pulsed preambles as in X-MAX[6], energy is reduced even further. However, as these MAC protocols reduce energy consumption in overhearing, they are still overkill for nodes that need to transmit once in a long time period, and are made with an active radio receiver in mind. If the active radio receiver would be on for 1 % of time, it still will be a waste of energy if a message is received once in a long time interval. In [12], a very broad description of MAC layers suited for wake up radios is given. Radio-triggered non cycling wake up radio is considered as most promising for ultra-low power radio communication [12]. In [37] and in [57], it is demonstrated that using a wake up radio is less energy consuming than several duty cycled MAC protocols, whereby the later states that this only counts for low traffic load.

2.2.5 Network Layer Techniques

In the network layer, it is assumed that physical layer and link layer take care of a reliable communication between two nodes. The network layer describes the protocol that creates a network of multiple devices. With multihop networks, long communication distances can be achieved. The network layer protocol describes the routing of message over multiple hops to deliver packets from one node to another. In custom made WSN, the network layer is sometimes omitted and only direct links between gateway and nodes are considered. Commercial products sell with techniques called ZigBee or Z-Wave and make use of the previous mentioned 802.15.4 MAC protocol certified by IEEE. This protocol consist of end-nodes and relay nodes. The end-nodes are most time asleep and are the lowest power nodes.

Another network layer technique is 6LowPan which ports the IPv6 layering towards WSN. This network layer can be build on top of 802.15.4 as well. The Routing Protocol for Low Power and Lossy networks (RPL) is a routing protocol on top of this 6LowPan layer presented by the IETFs ROLL working group [49]. In [38] a standardized communication stack using RPL is given. The RPL finds routes towards a sink which is the node connected to the internet or another higher subset. Routes are found from all nodes within the subnet. The graph that is created is called a Destination Oriented Directed Acyclic Graph (DODAG). A Directed Acyclic Graph (DAG) is a graph with directed links without cycles. Acyclic means that each node cannot return to itself from all paths originating from that node. The DODAG is destination oriented which means that the DAG ends in a certain sink node for all routes. Different metrics can be used to minimize hops or energy used. In [55] comparison of different energy aware metrics for RPL is given. Other algorithms for finding paths in a network are Dynamic Source Routing (DSR) and Ad-Hoc On-Demand Distance vector (AODV), which find a path on-demand. A more energy balanced approach between all nodes is proposed in [31] and compared to DSR and AODV. On-Demand path finding supports dynamic networks but has a lot of message overhead in low power WSN.

Multihop in Low Power WSN

With energy harvesting devices that are sleeping for a while, multihop becomes challenging because multiple nodes need to be awake and able to receive message. The transmitted message gets lost when a critical node is in sleep state. Commercial multihop protocols for WSN like 802.15.4 allow multihop only by relay nodes that are always awake. In [46], big networks are simulated with multihop transmission and it is shown that nodes can still achieve Quality of Service when part of the network is asleep. This is achieved by having multiple paths. Multipaths can significantly increase reliability by omitting the nodes that are asleep during a transmission and following another path. In [20], a multipath solution is proposed which finds multiple paths which can be used when a link fails. The authors in [36] and [45], propose a multihop system based on RF energy harvesting, where the minimum time between transmission should be higher than the minimum time a node needs to harvest. Based on distance to gateway, they divide nodes in their second work in bands and packets can be transmitted by multiple paths. However, collision rate in their work is quite high. Another technique for minimising energy consumption is clustering. Nodes transmit messages to a cluster node where these cluster nodes transmit to collected messages further in the network or directly to the gateway. Hereby energy consumption is limited because not every node has to transmit to the sink directly, this is for example done in [53]. In [25] it can be seen that this multihop solution using backscatter is energy harvested by solar panel and has sufficient energy to stay awake always. In [58] this is achieved using RF power available. Most current research and available protocols need multiple messages to achieve reliable multihop. Most research considers the harvested energy to be enough to be awake all the time.

Chapter 3

System Overview and Network Topologies

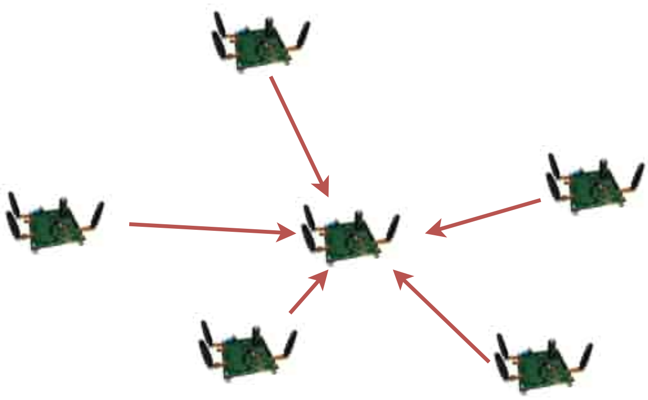
This chapter describes different topologies for a network of low power nodes with the aim to achieve time correlation between data measurements. At the end of the chapter, a schematic overview of the hardware for the required nodes is given.

3.1 System Topologies

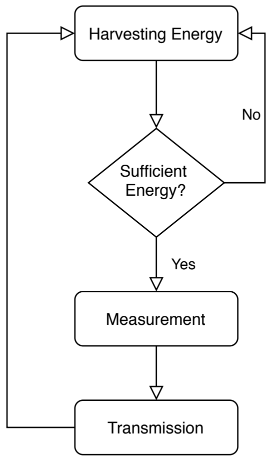
To collect and store the data from the network, a local gateway is used which connects the network to a database. This database can either be local or located on the internet. In Section 2.2 it is stated that a LP-WAN would be to energy consuming and therefore, the local gateway is chosen to limit energy consumption during data transmission. A node needs to decide when to perform a measurement and when to transmit it. Hence, a node needs to be able to receive information. To prevent nodes from continuously listening, the concept of a wake up receiver (WURx) as explained in Section 2.2.3 is used for message reception. This low power solution limits the receiving range of the nodes. This means communication distance between nodes, or from gateway to nodes is limited. Communication from node to gateway however is received with full sensitivity as the gateway uses an active receiver.

3.1.1 Transmit after Startup

The basic operation of an energy harvesting node that wants to report a measurement, is to startup when it has sufficient energy, perform a measurement, transmit it to the gateway and than turn off till it has sufficient energy again. The gateway is continuously listening and is able to receive the transmitted packet. Figure 3.1 shows an overview of the network topology and the Finite State Machine (FSM) of a single node. With all nodes randomly transmitting, the probability that different nodes transmit at the same time is low. However, an increase in network size or decrease in time interval between measurements, increases this probability of collisions. Due to errors in transmission or reception, there is a probability that messages get lost. The gateway has an active



(a) **'Transmit after startup' network topology.**



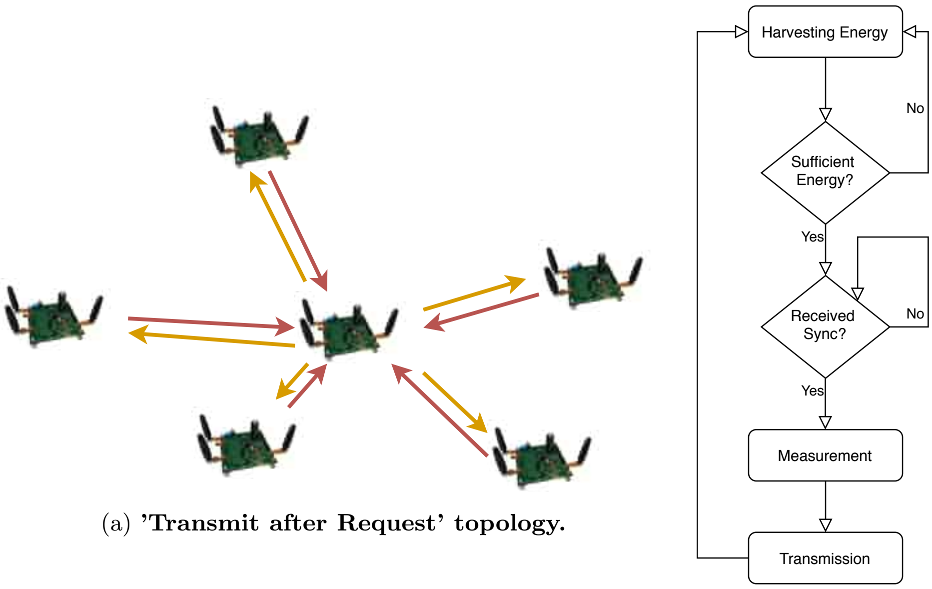
(b) **FSM of a single node.**

Figure 3.1: **'Transmit after Startup' topology. Measurements are collected randomly over time.**

receiver which usually has a sensitivity around - 100 dBm, and therefore, transmission range is as high as can be achieved with an active radio. Each time sufficient energy is available, it is used and as a result measurement reporting rate is maximal.
Advantage: Maximum data measurements. No dependency on other nodes. Maximal transmission range.
Disadvantage: No acknowledgement on arrival. No correlation in time with respect to other nodes.
Use Case: No time correlation between data measurements is required.

3.1.2 Keeping Track of Time

With the use of a clock that keeps track of time, a node can measure and transmit with a desired rate. If the clocks of different nodes are synchronized, measurements can be performed at the same time. The clock interval needs to be bigger than the needed time for all nodes to harvest sufficient energy. The clock has to run constantly and has to be as accurate as possible. Accurate clocks consume significant energy and have to be synchronized to other nodes. Low power clocks will start drifting from each other and to synchronize them, the nodes need to be able to receive synchronisation messages. This system is suitable for networks where the nodes have sufficient energy to run a clock continuously. The time interval should be short enough that clock drifting is limited within this time span. Collision avoidance is important in this topology considering the high probability that nodes transmit at the same time.
Advantage: Time correlation. Maximal transmission range. No dependency of other nodes.
Disadvantage: Energy consumption of clocks is significant. Clock needs to run continuously. Synchronisation between nodes is required to prevent drifting.
Use Case: Energy harvesting sensor networks with sufficient power for running



(a) **'Transmit after Request' topology.**

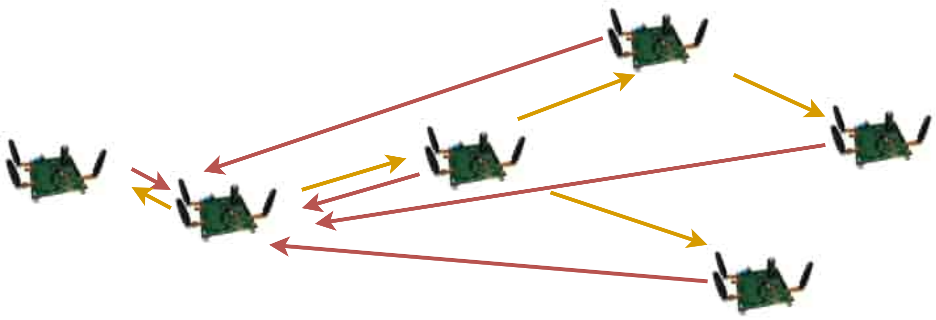
(b) **FSM of sensor node.**

Figure 3.2: **'Transmit after Request' topology. Achieving time correlation, but wake up range is limited.**

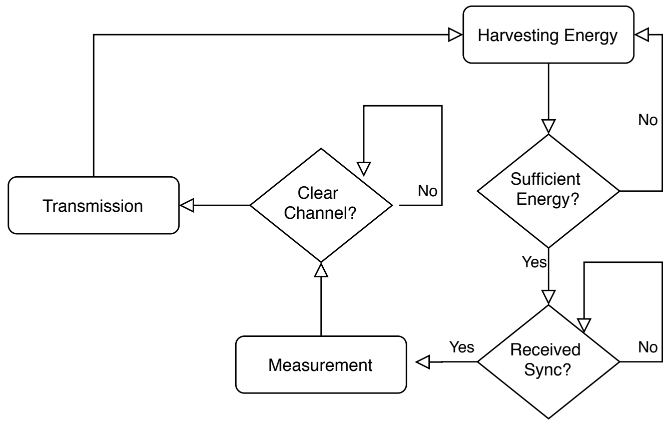
a clock and with sufficient power to have a limited time interval.

3.1.3 Transmit after Request

The WURx mechanism gives a node the ability to sleep and wake up when there is a message incoming. A node can get a measurement request by using this ultra-low power WURx. When a node has sufficient energy, it will turn on the WURx and start sleeping meanwhile waiting for a request message. Figure 3.2 gives the topology of this network and the FSM of a single sensor node. When the WURx consumes less energy than the continuously harvested power, the node will retain sufficient energy. The disadvantage of this method is the limited sensitivity in the low power WURx that is used. Because of the limited sensitivity, the communication range from gateway to nodes is limited to several meters, depending on the transmission power of the gateway. However, the gateway that has no energy constraints can transmit at high power while the transmission from the nodes is done at lower power. This saves energy for the nodes. When the gateway transmits at a maximum allowed transmission power of 20 dBm, the WURx with a sensitivity of -40 dBm can in theory receive at a theoretical maximum range of 25 m at 868 MHz using isotropic antennas, see Section 2.1.2. Requirement for the time interval is the same as with the 'Keep track of Time' topology. It should be bigger than the minimal time that all nodes need to harvest energy. To prevent collisions while keeping the delay between nodes as short as possible, the gateway should ask each node shortly after each other.
Advantage: Time correlation. No dependency on other nodes.
Disadvantage: Nodes need to be started to receive a message. Data rate



(a) **Topology.**



(b) **FSM of Sensor Node.**

Figure 3.3: **'Transmit after Request with Relaying' topology. Dependency on other nodes, but range is not limited anymore.**

limited to least harvesting node. Distance limited to sensitivity of WURx.
Use Case: Small network with nodes centered around the gateway.

3.1.4 Relay Request

Through relaying a request message, the maximum distance of the 'Transmit after Request' topology is extended. The topology of this network is shown in Figure 3.3. Transmitting data to the gateway will give a wake up message for a node that did not receive the first transmission from the gateway. Nodes further away cannot receive the gateway because of the limited receiver sensitivity. However, when they transmits themselves, the gateway can receive the transmission from the nodes because of the active receiver of the gateway. If the 'Transmit after Request' topology is used, the distance is the same same as in the 'Transmit after Startup' topology. The relaying of the wake up message to nodes further away gives a dependency for these nodes on nodes closer to the gateway. The relayed request message is the same message as the data message from the transmitting node back to the gateway. Each node can transmit once and therefore this wake up call can be done once, A direct request message to a single node is not possible. Therefore, nodes cannot directly be requested for a

measurement shortly after each other. Collision avoidance is important because of the high probability that nodes transmit at the same time. Collisions are avoided by clear channel assessment, but this needs to be done for the complete range that the gateway can receive. This clear channel assessment has to be done by an active radio. Hidden nodes at the other side of the gateway can still give collisions.
Advantage: Time correlation. Communication range as maximal as gateway sensitivity.
Disadvantage: Dependency on other nodes. Nodes need to be started to receive messages. Data rate limited to least harvesting node. High probability of collisions. Collision Avoidance difficult with hidden node problem.
Use Case: Networks that need time correlation in a bigger field.

3.1.5 Relay Request and Data

Instead of relaying the request message, the data measurements are forwarded from a dedicated end-node to the gateway. This has the advantage that the maximum distance is bigger than the maximal achievable distance from nodes to gateway. If the WURx is used to read the pattern in the message as well, collisions can only occur on the small WURx range. The hidden node problem can be solved by shortly amplifying the received signal, thereby shortly increasing detection range. Transmissions further away can be transmitted in parallel, and channel assessment is done with low power. An end-node within the network should be chosen which is able to start data collection rounds. Since nodes cannot transmit twice, a dedicated algorithm should make sure that to the gateway can collect all data. This should be done by letting all nodes wait for important incoming links in the network The topology is given in Figure 1.1. FSM is the same as the FSM in Figure 3.3 except that waiting for sync message needs to occur for all incoming links. It is required that nodes are awake during a data collection round, which is made sure by choosing the interval between data collection rounds bigger than the minimal time needed to harvest enough energy.
Advantage: Time correlation. Maximum network range is bigger than gateway sensitivity. Collision Avoidance can be done with low power including solving the hidden node problem. Transmissions can occur in parallel in the network.
Disadvantage: Nodes need to be started to receive messages. Data rate limited to least harvesting node. Nodes dependent on other nodes to be awakened and dependent on other nodes to forward their data. Message size increases for each hop.
Use Case: Nodes that need time correlation in a big field.

3.2 Chosen Topology

The topology of relaying data messages is chosen as system topology. Clocks are considered too energy consuming and therefore a request mechanism is needed. Without relaying messages, distance is limited, which limits the usability in networks. This, is fine in some cases, but usable cases are limited. The topology of relaying data messages, and thereby waking up other nodes, has more advantage in overall range and the reliability that data arrives. This increase in reliability is caused by limiting the complete reception to the sensitivity of the WURx.

This limits the range of other sources to collide to the transmission and gives a lower sensitivity for noise as well. Collision avoidance is performed on this limited range and the hidden node problem can be solved. The big challenge however will be to minimize the dependency on other nodes.

3.3 System Overview

This section describes an overview of the implementation of the sensor nodes. The nodes are powered by an energy harvesting source and receive data using a WURx. They can perform a sensor measurement and have an active transmitter to report this measurement. With this implementation, the 'Transmit after Request' with and without relaying topologies can be formed. The chosen topology, as described in Section 3.1.5, will be tested with this implementation. With harvesting from Radio Frequency (RF), harvested power is usually very limited. Hence, this energy source is chosen. It gives a good way to test if the system runs under limited power conditions. Besides, the techniques of RF harvesting are used in a WURx implementation as well, which in fact 'harvests' the transmitted signal.
Ambient RF sources that are promising energy sources to harvest power from are Digital Television (DVB-T) for its high powered transmission and GSM for its wide availability. In the 900 MHz band of GSM, the downlink frequency is from 925 MHz to 960 MHz. A harvester tuned to 935 MHz with 50 MHz bandwidth can be powered by a dedicated 915 MHz source as well. The 915 MHz is an Industrial, Scientific and Medical (ISM) frequency and is used for testing in the lab. FM radio harvesting is promising in range, but requires long antennas due to its low frequency of 100 MHz. Analog television is even achieving more range at a higher frequency but is replaced by digital television in many countries. In Section 2.1.2, an overview of the maximal potential of these sources is given. Is is chosen to tune the circuit to the GSM band and test whether the nodes can be powered at the campus. Although the range of GSM for energy harvesting is limited, antennas are placed all around us. For testing inside, a dedicated 3 W RF power transmitter at 915 MHz is used.

3.3.1 Hardware Overview

The needed subsystems and their interconnections are given in Figure 3.4. The system is designed around a CC1310 System on Chip (SoC) which consists of both an integrated Cortex M3 core and a RF Core. The RF core is suitable for sub-GHz data communication. Power Management IC (PMIC) is the ADP5090 which stores the harvested energy into a 4.7 mF supercapacitor. The PMIC cycles the supercapacitor between 2.3 V and 2.9 V, which gives 7.3 mJ of energy that can be used. At 2.9 V, the system is started and most energy is consumed during the next data collection round. The system is shutdown when a data collection is finished or when the capacitor drops below 2.3 V. Two RF harvesters are placed on the board. One serving as energy source and the other to detect the signal for the WURx. The SHTC3 temperature sensor is chosen to demonstrate the functioning of the system. This sensor consumes 1 μJ during each measurement. Design of parts of 1,2 and 3 is explained in Chapter 4; In Chapter 5 and Chapter 6, parts 7 and 8 are explained.

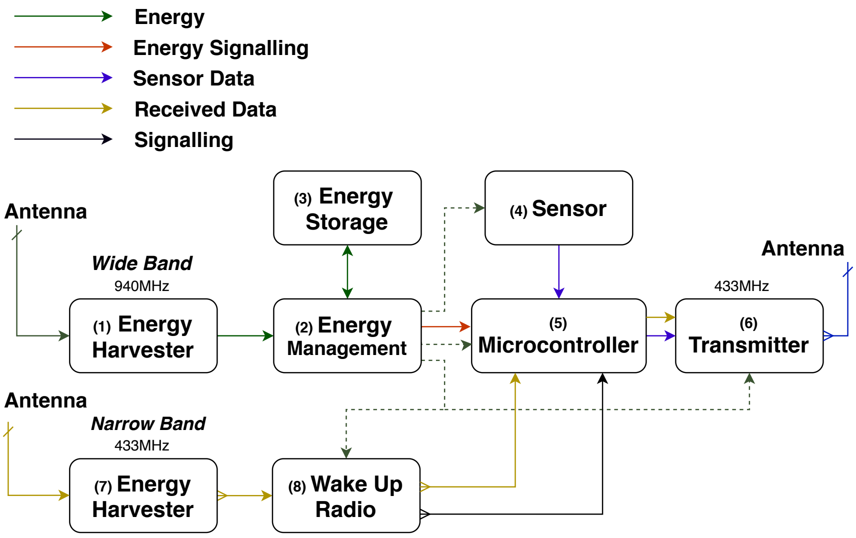


Figure 3.4: **Global Hardware overview of Sensor Node.**

3.3.2 PCB Design

A final PCB implementing the whole system is designed according to the system overview in Figure 3.4. The PCB is manufactured and tested. The results of the functioning of the PCB is discussed in the following chapters. The PCB is shown in Figure 3.5. Correct functioning of all parts together is shown in Chapter 8. The proposed idea to achieve time correlation between data measurements of different nodes is demonstrated functioning with these implemented nodes.

3.4 Communication Overview

The communication process is divided in abstract layers according to the OSI Model [11]. All layers have their own responsibility for a subpart of the communication process. In Figure 3.6 the OSI Model of the communication algorithm for this system is shown.

3.4.1 Physical Layer

In the physical layer, the physical part of the communication is hosted. A transmission is done using a 10 dBm OOK transmission using the CC1310 SoC. An ultra-low power WURx, that wakes up the system when a transmission is detected, is used for receiving transmissions. The MCU is used to read out all bits in the received signal. Bitrate is selected to be 8 KHz. The physical layer is responsible for correct bit detection and bit synchronisation. This layer is described in Chapter 5.

3.4.2 Link Layer

The link layer is responsible for the correct arrival of a message between two nodes. Collisions are expensive as a node cannot transmit twice. Hence, this

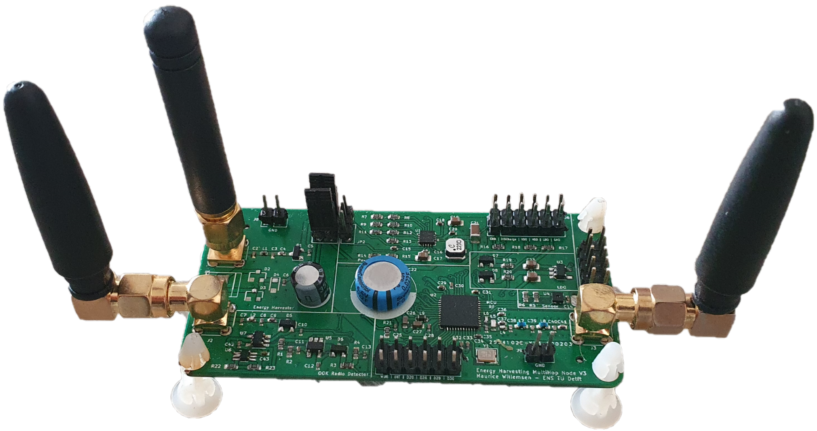


Figure 3.5: **Designed PCB of implemented node.**

Application Layer	Data Protocol	Path Protocol	
Network Layer	Forward Protocol		Exploring Protocol
Link Layer	Link Protocol		
Physical Layer	Wake Up OOK Detector	WUR + Active Radio	

Figure 3.6: **Abstract Layer Model of Communication according to OSI Layers.**

layer is important in the overall robustness of the system. In a multihop solution, the bit error in the link layer will be multiplied for each hop. A collision avoidance mechanism with a random backoff time between 50 ms and 150 ms is used to avoid collisions. An amplifier is used to shortly amplify the received signal to detect a transmission from a hidden node. This layer is described in Chapter 6.

3.4.3 Network Layer

The network layer hosts the multihop algorithm that finds a Directed Acyclic Graph (DAG) of all nodes. This DAG is important in order to collect all data in the network considering the requirement that all nodes can only transmit once. The exploring protocol finds this DAG and the data forwarding protocol uses it to collect all data in a data collection round. This algorithm is described in Chapter 7.

3.4.4 Application Layer

The application layer protocol depends on the use case of the system. This layer is responsible for transmitting the specific data from the nodes and for storing it in the database. This layer specifies how measurement data are ordered in the message. Because the system is hopping by all nodes which include their data, packet size grows for each hop. This increases energy consumption by nodes that need to transmit these messages. Without compression, data collection would add measurement + node ID for each node. Hence, there is a linear correlation between network size and message size. A technique to minimize the length of the data would be to only transmit the difference between the measurement of the first node and the measurement of the current node. This only works assuming that a measurement is not completely independent from measurements of other nodes. This gives less databits, but precision is kept the same. A third technique considers that for some use cases it is sufficient to only know if a value is above a certain threshold, either a specific threshold or the starting value. With this technique a single databit is enough. However, the ID of the node still has to be transmitted for every node. If the same length for all nodes is always transmitted, and nodes place their data on the bit index of their node ID, than no node ID has to be transmitted for every added value. This makes all data transmissions equal in length instead of increasing data size along the network. This is more efficient if the node ID length is long in respect to the data part. Besides, an additional bit has to be included for all nodes to indicate that they have updated the value of their node. Using this indexing of data is efficient when using the comparison technique and gives two bits of data for each node, one for indicating the comparison and one to indicate that the value is set.

In the demonstrated system, the system has a maximum of 32 nodes. The temperature of the first node is transmitted in complete format, in 2 bytes. The other nodes transmit the difference to this node in 7 bits with an accuracy of 0.1°C. So in total, the maximum difference can be $-6.4\,°C$ till $+6.4\,°C$, and each node is $5+7$ bits $= 1.5$ bytes. The length of the application layer becomes: $\lceil 2 + N \cdot 1.5 \rceil$. Maximum application layer size is therefore 47bytes for N = 30. N = 30 is the maximal case for a total of 32 nodes as the first node is placed separately and the last receiving node is not included in the transmission.

Chapter 4

RF Energy Harvesting and Energy Modelling

RF energy harvesting is discussed in this chapter. A RF energy harvesting circuit and a power management IC are used to harvest energy from RF waves. The harvested energy is stored in a capacitor. When the capacitor is sufficiently charged, the system will be started, and the MCU controls how long the system is on. Furthermore, an energy model for the energy consumption of the nodes is given in this chapter. This energy model is needed to determine the time interval for the data collection rounds.

4.1 RF Energy Harvesting

The technique for harvesting energy out of RF waves is not novel. However, commercial products that are specialised on RF harvesting are scarce. Available Power Management ICs (PMIC) for a broad range of energy harvesting sources need a DC input signal. Such a PMIC is chosen and the circuit for converting the RF signal to a DC level is made using the theory described in Section 2.1.2. This same circuit structure is used in the design of the WURx, described in Chapter 5. The design of the RF energy harvester is based on several requirements which are described in the next section. The design is implemented and tested and results are given. A schematic overview of the design that is used to harvest and store RF energy is given in Figure 4.1.

4.1.1 Requirements

The following requirements apply to the design of the RF energy harvester and the chosen Power Management IC:

- The circuit must harvest the energy out of the RF waves.
- The circuit must be completely passive, i.e. there is no other power available than the harvested power.
- The conversion efficiency must be optimized for low input power ranging from -15 dBm to -5 dBm. Lower input power is not sufficient for the PMIC to boost the signal. Higher input power would still give enough power when the conversion efficiency is lower for that range

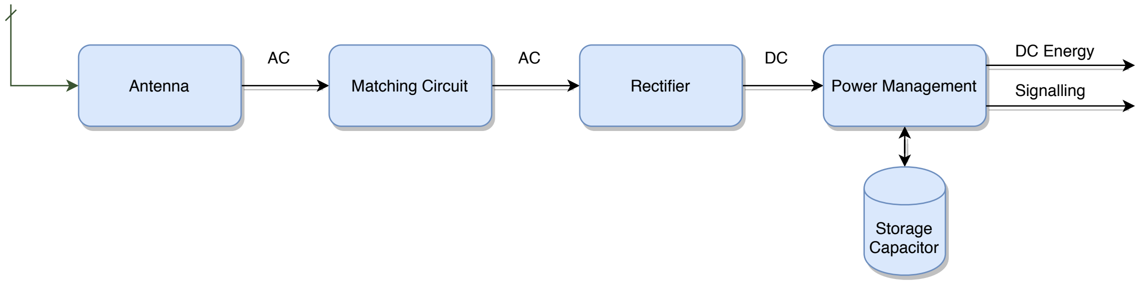


Figure 4.1: **Schematic overview of the RF energy harvester and power management.**

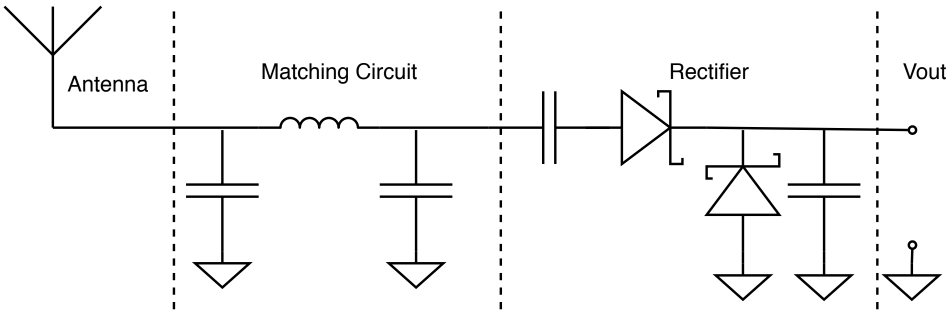


Figure 4.2: **Circuit design of RF Energy Harvester.**

- Center frequency of the system should be 935 MHz with a bandwidth of 50 MHz. Power can be harvested from the 900 MHz GSM band and from a dedicated 915 MHz transmitter.
- A Power Management IC must boost the voltage of the harvested signal and store the harvested energy for later use.
- When sufficient energy is harvested, an indication signal must be raised, and the system must be started.
- The output DC voltage of the PMIC, V_{PM}, must be higher than the minimal voltage, V_{min}, that the system can run on.
- Sufficient energy must be stored to make sure that V_{PM} retains above V_{min} during system operation. Therefore, maximal energy consumption during system operation must be known.

4.1.2 Circuit Design

The circuit structure is shown in Figure 4.2. Matching circuit is centered at 935 MHz with a bandwidth of 50 MHz. Using this frequency, the system can be tested under ambient RF conditions, by harvesting power from the 900 MHz band of GSM. A dedicated 915 MHz transmitter can be used as well to test the system indoor. The bandwidth of 50 MHz results in a desired Q-factor of 18.8 in the matching circuit according to (2.6). Monopole antennas are used and therefore no BalUn design is needed.

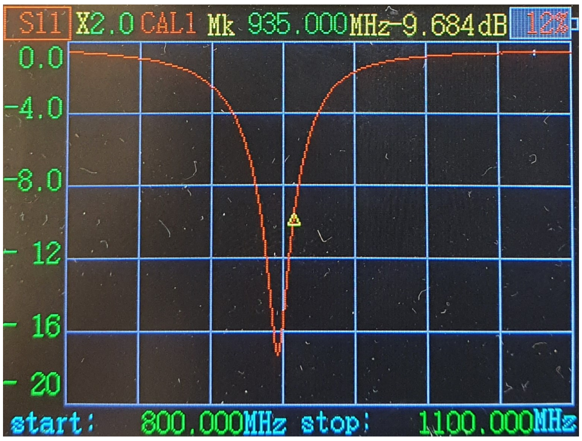


Figure 4.3: **S11 graph of one the PCBs. Measured with a VNA.**

Rectifier

Maximal efficiency at low input power is achieved by preventing loss in the schottky diodes that are used to rectify the input signal. A single stage voltage multiplier is chosen as rectifier. This type of rectifier is called a voltage doubler as, in theory, the output of this voltage doubler will be a DC level of twice the amplitude of the input AC level. A single stage voltage multiplier uses less schottky diodes, and as a result less energy is lost. However, the output voltage stays lower. Testing with 2 and 3 stages resulted in a higher voltage gain, but in a decrease of the energy efficiency. The SMS7630 schottky diode is used, which is suitable for ultra-low power RF rectification. The SMS7630 has a low typical junction capacitance of 0.3 pF. Low capacitance is important for minimizing the influence on the matching circuit.

Matching Circuit Values

The matching circuit is selected to be a pi-matching circuit. A pi-matching circuit has more control on Q-factor and the center frequency. Values for the matching circuit are calculated and simulated. Simulations with real values of the used schottky diodes are done to see the influence of the schottky diodes. The values of the matching circuit are changed accordingly. In the PCB design, attention is payed on giving the traces the characteristic 50Ω impedance to match to the antennas. The ground plane is covering the whole backside of the PCB. Around the RF harvester, there is a ground pour as well. With the simulated values of the matching circuit, the PCB is implemented and tested with a Vector Network Analyzer (VNA), to check the return loss of the harvester. It turned out, as expected, that the PCB design still influences the center frequency and the bandwidth. According to the reflection graph with respect to frequency, the s11 parameter, the added capacitance of the PCB is estimated, and the values are changed accordingly. Even between different PCBs, the frequency is shifted with maximal 10 MHz, due to the intolerance in the passive components. In Figure 4.3, the s11 graph, measured on one of the PCBs with the VNA, is given. The center frequency is shifted with 6 MHz on this PCB.

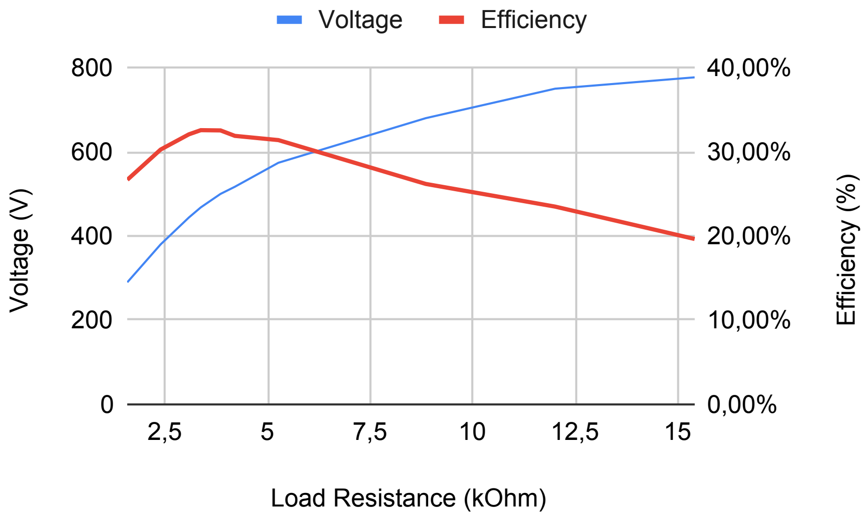


Figure 4.4: **Measured voltage over load. Efficiency is calculated with respect to load resistance. Input power is -7 dBm.**

4.2 Power Management

The Analog ADP5090 is chosen as PMIC as it has a low startup voltage of 380 mV, and an operating voltage of 80 mV. It can run with an input power of 10 μW.

Maximum Power Transfer

Maximum power transfer is obtained by matching the impedance at the input of the PMIC to the output impedance of the rectifier. Impedance from the input monopole antenna is 50 Ω. As seen from the PMIC, the matching network and the voltage doubler in between the antenna and the PMIC do increase this impedance. In both matching network and voltage doubler there is a voltage gain and therefore the impedance is increased. Maximum power transfer is tested with different loads connected to the circuit. The input signal is created by a signal generator which has an impedance of 50 Ω. Measured voltage and efficiency with respect to different loads are given in Figure 4.4. The maximum power transfer is obtained at a load of 4 kΩ. This gives a gain factor of 80 through the harvesting circuit. Considering [35], the gain factor of the single stage voltage doubler is 5.3. This gives a measured gain factor for the matching circuit of 15.1 which corresponds to a bandwidth of 62 MHz at 935 MHz. This is slightly higher than expected, and is due to added capacitance in the circuit. Voltage at this maximum power transfer point is 500 mV for an input of -7 dBm. The open voltage is 1 V. As a result, a Maximum Power Point (MPP) ratio of 0.5 is obtained. At -15 dBm input power, the open output voltage is 410mV. With a load that results in a MPP of 0.5, this voltage becomes 205 mV. With the 4 kΩ this results in a harvested power of 10 μW over the given load. The Analog ADP5090 is able to operate from this voltage. The MPP is set by a

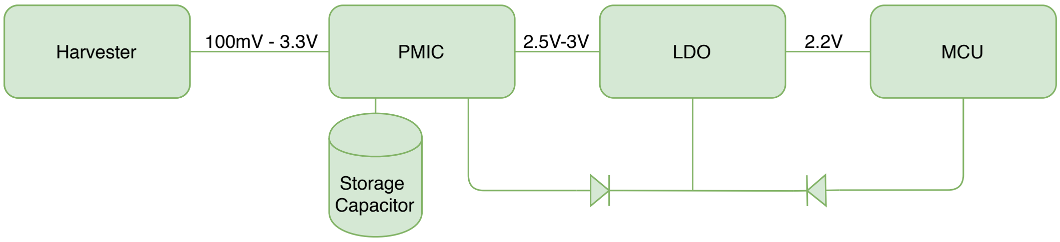


Figure 4.5: **PMIC Overview. MCU can control how long the LDO is on.**

resistor division, and is set to 0.5.

Power Good

The ADP5090 PMIC provides an indicating signal if the energy in the capacitor is sufficient. An ultra-low power low dropout voltage regulator (LDO), with a feedback loop from the MCU, is added. This is to generate a stable voltage to the system as the capacitor voltage will fluctuate, and the feedback is to let the MCU keep control on how long it needs to be powered. When the storage capacitor has sufficient power, the PMIC sets a 'PGood', signal and the LDO and MCU are turned on. Now that energy is used, the capacitor will discharge, and the 'PGood' will be switched off. Nonetheless, the feedback from the MCU keeps the LDO on. A structural overview of the PMIC in the system is shown in Figure 4.5. The MCU can decide to switch off the LDO when it finished its operation. Diodes prevent energy loss from a HIGH to LOW output of either PMIC to MCU or MCU to PMIC. The voltage levels from PMIC and MCU differ because of the LDO in the middle. Hence the diodes prevent energy flow between the different voltage levels. The LDO sets a voltage of 2.2 V to the circuit. The MCU is working at 1.8 V, so this 2.2 V is sufficient. The 'PGood' signal is set when the capacitor reaches 2.9 V. Attention has to be made to the input signal of the LDO. The datasheet states that the voltage of the select signal should be $> 70\,\%$ of the voltage of the power input signal. With the maximum condition of the MCU to hold the input signal being slightly below 2.9 V, the input of the select signal should be at least working from $2.9\,\text{V} \cdot 70\,\% = 2\,\text{V}$ and higher. A schottky diode is selected for its low dropout voltage of 150 mV. With considering the voltage drop in this diode, the minimal voltage of the select signal should be 2.15 V. Therefore, the voltage of 2.2 V of the select signal from the MCU, is sufficient to keep the LDO on. The LDO gets a pull down resistor to prevent floating when both PMIC and MCU are pulled down while the diodes prevents signalling this to the LDO.

Storage Size

The maximum application layer size for the demonstrated system is 47 bytes, as stated in Section 3.4.4. Including headers, the maximum packet length will be 70 bytes in total. Transmission is done with OOK with a datarate of 8 kHz at 10 dBm, as described in Chapter 5. This results in a maximum of 70 ms transmission time. CC1310 consumes 11 mA in this mode. LDO sets the MCU voltage at 2.2 V, but the voltage gap between the output of capacitor uses the same current. So, the voltage in the energy calculations must be 2.9 V as worst case after starting. The capacitor can charge further to higher voltages, but in that case, more energy will be available as well. The transmission consumes at maximum $0.07\,\mathrm{s} \cdot 2.9\,\mathrm{V} \cdot 11\,\mathrm{mA} = 2.2\,\mathrm{mJ}$. Energy consumption due to processing and receiving depends on the number of nodes. According to the energy model in Section 4.4, the total energy consumption is considered to be maximal 4 mJ in worst case scenario. Temperature measurement is 1 μJ and is negligible. A total of 4 mJ available energy is enough for one round. Energy in a capacitor is calculated by (4.1). The capacitor size is selected according to (4.2). The 'PGood' signal is set at 2.9 V, and the LDO will work until the capacitor drops to 2.3 V. Therefore, the capacitor size should be $> 2.6\,\mathrm{mF}$.

$$W = \frac{1}{2} C V^2 \tag{4.1}$$

$$C = \frac{E}{\frac{1}{2}(V_H^2 - V_L^2)} = \frac{5\,mJ}{\frac{1}{2}(3^2 - 2.3^2)} = 2.6\,mF \tag{4.2}$$

Start Up Circuitry

The PMIC itself has to startup by charging the capacitor until 1.9V. When started it runs its main boost converter on the voltage level of the capacitor. The cold startup circuit is less efficient than the main boost converter. Therefore, the input power needs to be higher during this period. Accordingly, the minimal voltage level from the RF harvester needs to be higher. However, when the IC is started and input power is insufficient, the IC completely shuts off when the capacitor drops to a level of 2.2 V. Only the discharge leakages make the supercapacitor discharge. Through testing, it turned out that the capacitor could survive a whole day without input power, while staying above the 1.9 V startup threshold.

4.3 RF Harvesting Results

This section gives the results of the harvester in combination with the Power Management IC. Figure 4.6 shows the efficiency achieved with respect to input power. This test is done by using an signal generator that generates the input signal. The efficiency of the harvester is measured by measuring the voltage across the optimal load, as given in Figure 4.4. The power is calculated according (4.3). The total charged power in the capacitor is measured by measuring the voltage of the capacitor at two different times, and divide their energy difference by the time in between as given in (4.4). This method tests the energy that is actually stored over time in the capacitor, and therefore, considers all quiescent currents and all leakages. As can be seen, the PMIC needs a certain power to be able to boost the input voltage. Between -15 dBm to -10 dBm, the system is providing energy to the capacitor, but the efficiency is low. At -15 dBm, 1μW is provided, at -12dBm 6 μW and at -10 dBm 16 μW is provided. The RF harvester itself has >10 % efficiency at -20 dBm. This is comparable to other related work, see Section 2.1.2.

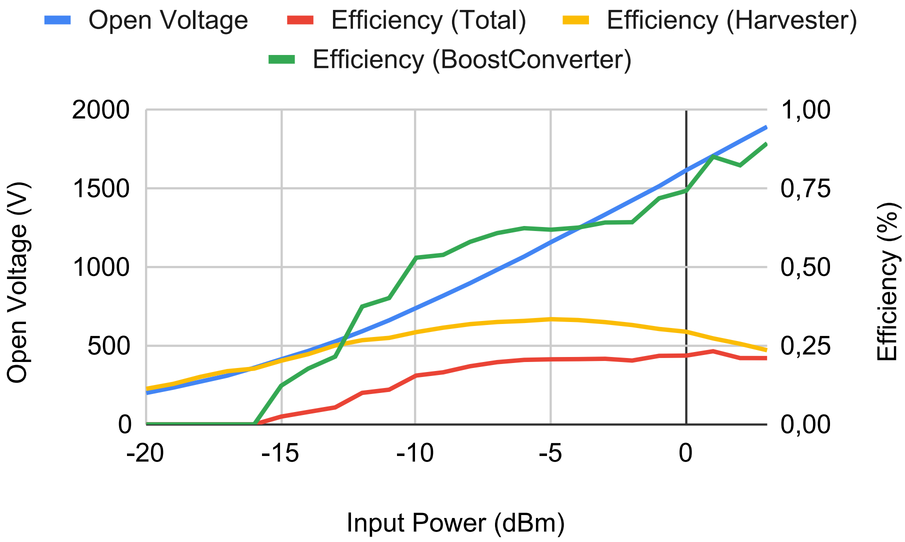


Figure 4.6: **Efficiency of RF energy harvester with respect to different Input Power.**

$$P = \frac{V^2}{R} \tag{4.3}$$

$$P = \frac{\frac{1}{2}C \cdot (V_2^2 - V^2)}{T} \tag{4.4}$$

Real Testing

On the nodes in the network setup, a basic compact quarter-wave antenna is placed with a gain of just 1dB which is a very limited gain. Distance and obtained power could be increased by paying attention on good antenna design. However, antenna design is omitted in this thesis work. On a distance of 2 m from the transmitter of 3 W, transmitting at 915 MHz, a open voltage of 800 mV to 1200 mV is measured. This difference in open voltage, and thus obtained power, results from the alignment of the nodes in the RF beam and the orientation of the nodes themselves. The difference that originates from the orientation makes clear that the antenna with the ground plane of the PCB is not optimal, as the ground coupling is not good in all directions. The 800 mV to 1200 mV corresponds to -4 dBm to -8 dBm input power, based on measurements done with the signal generator. Input power is slightly below the theoretically expected -2 dBm to -3 dBm according to (2.3). This is due to a difference in matching frequency and non ideal coupling between signal and node.
Placing the nodes further away at a distance of 4 m, resulted in -14 dBm to -10 dBm input power, depending on the orientation. The theoretical expected input power on this distance is -9 dBm to -8 dBm.
To achieve higher distance, one node is tested with a 6dB directed antenna which gave better results. When oriented correctly, this antenna not only has a

higher gain, it has as well a better ground coupling due to an own ground plane. The distance was increased to 10 m, where the node was still slowly charging.

Ambient RF Testing

Testing on GSM frequency on the TU Delft campus resulted in a maximum range of around 140m where the node was charging with the monopole antenna. With the 6dB directed antenna, the maximum achieved distance was around 240m where the node was still charging. However, for these results, Line of Sight (LoS) was necessary, and the nodes needed to be placed in the center beam of the antennas. On the campus, the open voltage of the harvester was measured to be between 50mV and 730mV, and corresponds to a maximum input power of -10 dBm. This is a broad range of input powers, and despite that it is possible to power the nodes, attention has to be given towards the placement of the nodes when a network is setup. Besides, dedicated antenna design with directed GSM antennas should increase harvesting range.
A single node was tuned to a frequency of 700 MHz, and was used to test harvesting on DVB-T signals. Because of the higher and constant power transmission of these stations, higher distance is obtained. With a basic TV antenna and LoS towards a 10kW DVB-T transmitter, the maximum achieved range was 1.1 km. At this distance open voltage of the harvester was measured as 430 mV and the node was still slowly charging.

Conclusion

A RF harvester is implemented and tested. Together with the Power Management IC, a capacitor is charged over time, and when sufficient power is available, it switches on a LDO for further circuitry. The MCU can control how long to draw power from the PMIC. The minimal input power to get the capacitor charging is -15 dBm. From -10 dBm on, charging is done with an overall efficiency of 25 % including discharge leakages. This is comparable to state of the art papers, see Section 2.1.2. Testing is done with a 3 W RF transmitter, on ambient RF of a GSM transmitter and on ambient RF of a DVB-T transmitter. On limited range of the transmitters, the capacitor could be charged. Dedicated antenna design and proper ground coupling is needed to further improve harvested energy and increase range. When paying attention on the location of transmitters and on the placement of the nodes, it is possible to charge the capacitor and run a node on it. This work shows that it is possible to harvest energy from an ambient RF source with basic antennas and a custom designed PCB. As seen in the related work in Section 2.1.2, CMOS design can improve efficiency. A PMIC with integrated rectifier and a thoroughly designed matching circuit can lower the minimal input power with a few dBm. Together with a directed high gain antenna, harvesting range could be improved. RF waves are a potential energy source for powering sensor networks. However, it will always be necessary to research the environment for potential RF sources RF as harvesting from them remains limited to a certain range from the transmitters.

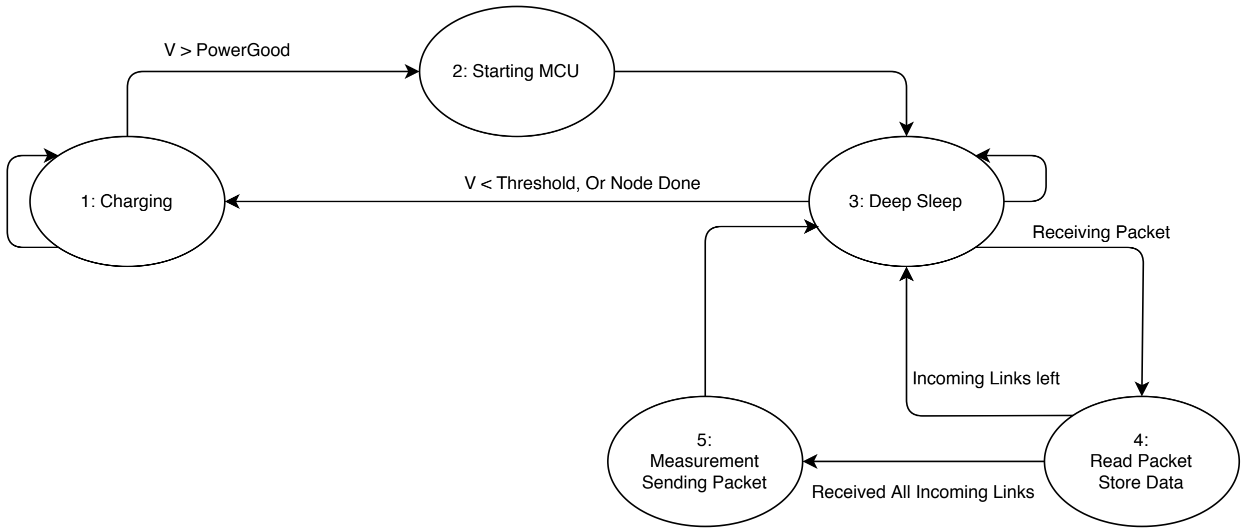


Figure 4.7: **FSM model of a Node in the System.**

State	Power Consumption	P	T	N
1	0	0	T - t_on	
2	$P_{Sleep} + P_{Startup}$	8 mW	55 ms	1
3	P_{Sleep}	2 μW	t_on	
4	$P_{Sleep} + P_{RX}$	1 mW	[30, 80] ms	[0, N-1]
5	$P_{Sleep} + P_{TX}$	33 mW	[30, 80] ms	[0, 1]

Table 4.1: **Energy Model Values.**

4.4 Energy Modelling

During lifetime, the sensor node will be in different states. In Figure 4.7, the FSM of the node is given. Each state of the node has a certain power consumption. In Table 4.1, the power consumption and the expected time to be in the state are given. For fixed time states, the amount of repetitions during time interval T is given. For this model, it is considered that the network algorithm is a reactive algorithm. This means that processing of data and state updates happens upon reception of other messages. Transmission occurrence is modelled as [0,1] times, because the nodes will transmit once within a round, and only if they are awakened. The amount of receptions is at most 1 message from all other nodes. False wakeups can occur, but no synchronisation will be found for them and the reception is quickly quit and energy consumption is low. The receptions are modelled as [0,N-1]. Time for both transmission and reception is modelled as [30,80] ms. Processing time before a transmission of after a reception is 10 ms, and the remaining time corresponds to the length of the packet. The length of the packet is given by the data that is within the packet and depends on the amount of previous nodes. Maximum packet length is considered as 20 - 70 bytes at a datarate of 8 KHz, which is explained in Section 3.1.5 and

Section 5.2.3. A node has sufficient energy for a round if in a round:

$$E_{Harvested} > E_{Consumed} \tag{4.5}$$

While harvested power is:

$$P_{Harvest} > P_{Sleep} \tag{4.6}$$

For time period T the requirement is:

$$T > \frac{E_{Consumed}}{P_{Harvest}} \tag{4.7}$$

$$T \cdot P_{Harvest} > t_{on} \cdot P_{on} + t_{start} \cdot P_{start} + N_{RX} \cdot t_{RX} \cdot P_{RX} + N_{TX} \cdot t_{TX} \cdot P_{TX} \tag{4.8}$$

Where $P_{Harvest}$ is the power after rectification and boosting. The requirement for the Time Period T becomes:

$$T > \frac{t_{on} \cdot P_{on} + t_{start} \cdot P_{start} + N_{RX} \cdot t_{RX} \cdot P_{RX} + N_{TX} \cdot t_{TX} \cdot P_{TX}}{P_{Harvest}} \tag{4.9}$$

For the whole system to be sufficient, the least harvesting node under worst case conditions has to be considered. The worst case is when all nodes need to transmit to a single node, which then needs to transmit all their measurements to the gateway. In the case of a maximum of 32 nodes, 31 nodes can be received by this worst case node. However, the length of the messages of these nodes now decreases to a minimum because they do no relay each other. Worst case transmission packet is full length because of relaying data of all previous nodes. Worst case for t_{on} is less obvious. Maximal energy consumption is when worst case of $t_{on} = T$, because when the capacitor retains above 2.9 V, the node stays on and power consumption is higher. However, this means that the capacitor has still a sufficient amount of energy after previous rounds, which does not occur when the limit for T for the worst case node is chosen. The limit occurs when synchronisation message arrives slightly after the node turns on and when the node turns off after transmission. This is a short time compared to T, and the power consumption is low compared to the other states. Therefore the energy this consumes is negligible compared to the other states. Hence, in the worst case condition, t_{on} is short, and its energy consumption is negligible. With N = 32, T is chosen according to the following equation:

$$T > \frac{55\,ms \cdot P_{start} + 31 \cdot 30\,ms \cdot P_{RX} + 1 \cdot 80\,ms \cdot P_{TX}}{P_{Harvest}} = \frac{4 \cdot 10^{-3}}{P_{Harvest}} \tag{4.10}$$

With this, it is calculated that the worst case energy consumption is 4 mJ. In Figure 4.8, the energy in the capacitor of 4 nodes is simulated. The nodes in this simulation setup consume 0.75 mJ when they startup, and 3 mJ, during the data collection. Continuous power consumption when the nodes are active is 2 μW. Interval between collection rounds is 12 minutes. Node 1 that harvests 4 μW does not harvest enough power to run all rounds. The others do, and node 4 retains sufficient energy to stay on continuously under these circumstances.

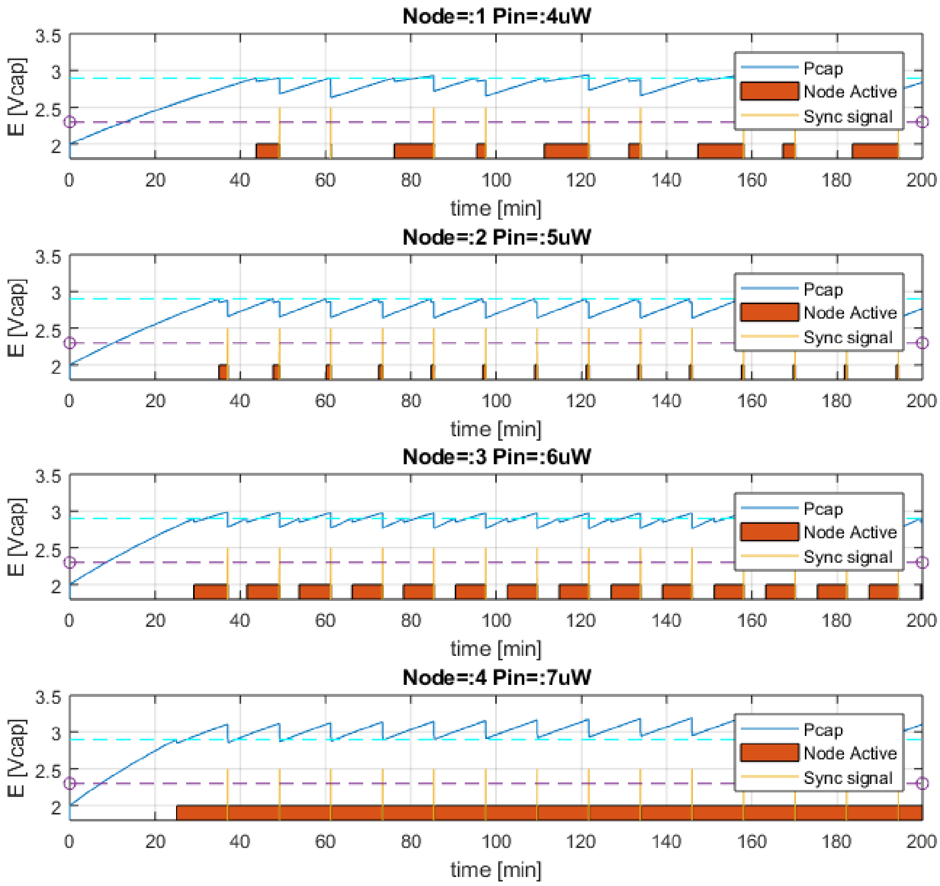


Figure 4.8: **Simulation of the energy in the capacitor of 4 nodes with different harvested power. Node 1 does not harvest enough power for each round. Time interval is 12 minutes.**

4.4.1 Probability

Previous calculation for time period T is for a constant power input. In real scenarios $P_{Harvest}$ will be a function over time with an expected value and a variance due to uncertainty in RF circumstances. Let this power over time be given by $P_H(t)$, than the harvested energy over time will be given by $E_H(t) = \int_0^t P_H(\tau)d\tau + E_0$. The expected value of E_H over time period T, is the mean power multiplied by T with a certain variance. The variance in the received power raises the probability that the harvested energy differs after time T. The harvested energy during time period T is modelled as a gamma distribution process as shown in [8], and is calculated as follows:

$$f_{E_H(T)}(x) = \frac{\beta^{-\alpha T}}{\Gamma(\alpha T)} x^{\alpha T} e{-}\beta x \tag{4.11}$$

Where the gamma function is given by:

$$\Gamma(\alpha) = \int_0^{inf} x^{\alpha-1} e^{-\alpha x} dx \tag{4.12}$$

The mean power, expected value and variance are given by:

$$\overline{P_r} = \alpha/\beta \tag{4.13}$$

$$E[f_{E_H(T)}(x)] = \overline{P_R} T \tag{4.14}$$

$$var(f_{E_H(T)}(x)) = \alpha^{-1} T \bar{(} P_r^2) \tag{4.15}$$

To find the probability that after time T the harvested energy is lower than μ, the Cumulative Distribution Function (CDF) is needed. This CDF is given by:

$$F_{E_H(T)}(\mu) = P(f_{E_H(T)}(x) < \mu) = \int_0^{\mu} f_{E_H(T)}(x) d\mu = \int_0^{\mu} (\frac{\beta^{-\alpha T}}{\Gamma(\alpha T)} x^{\alpha T} e{-}\beta x)\, dx \tag{4.16}$$

Let μ be the amount of energy that is considered as sufficient energy. Than, the probability that sufficient energy is harvested after time T is given by $1 - F_{E_H(T)}(\mu)$.
However, this considers that each round is started with no energy, and that no minimum energy is needed. In the system, a capacitor is used with energy level $E_C(t)$. This capacitor has a minimum energy level E_{MIN}, whereafter the PMIC turns off the system. Furthermore it has a maximum energy level, E_{MAX}, due to overvoltage protection. Besides, E_{GOOD} is the energy level in between these, to indicate that sufficient energy is available. Having a round where harvested energy is not sufficient, does not necessarily mean that the system cannot run as a surplus of energy from a previous round can be used.
The energy in the capacitor is therefore:

$$E_C(t) = min(\, max(\, E_C(0) + E_H(t) - E_D(t),\, E_{MIN}),\, E_{MAX}) \tag{4.17}$$

Where $E_D(t)$ is the consumed energy, and is given by:

$$E_D(t) = (\lfloor \frac{t}{T} \rfloor + 1) \cdot 4.3mJ \tag{4.18}$$

Paper [8] gave a good start to the energy model, but in their case, the node is on as long as the energy is above the minimal level. The node runs a task each time period T until the battery reaches level E_{MIN}. After that, the battery needs to charge to E_{GOOD} and the timer starts again. Therefore, they calculate time till first unfeasible task. In this work, the nodes need to be at level E_{GOOD} each time period T, in order to run a data collection round. After time period T, the nodes shutdown.
Choosing the time period T so that μ is $E[f_{E_H(T)}]$, gives 50 % change that in a round sufficient energy is harvested. To increase this probability, time period T is chosen bigger than the exact expected time. However, using $1 - F_{E_H(T)}(\mu)$ to calculate the probability considers a single round of harvesting energy. As stated, with choosing T so that $\mu < E[f_{E_H(T)}]$ surplus of energy in previous rounds is expected. And therefore, the probability is higher that $E_C(t) >$

E_{GOOD} at $t = nT$ for $n = 0, 1, ...$
Considering that all previous rounds could be run, at time $t = nT$ for all n, the probability that $E_C(t) > E_{GOOD}$ is given by the probability that the round harvested enough energy, $1 - F_{E_H(T)}(\mu)$, plus the probability that the previous rounds harvested the energy that is missing in this round. Over time, this basically steepens the gamma distribution function, and thereby the probability that energy is sufficient, is increased. This is given by:

$$P(E_c(nT) > E_{GOOD}) = P((E_0 + n \cdot f_{E_H(T)} - \cdot E_D(nT)) > E_{GOOD}) \quad (4.19)$$

However, this considers the probability over time, and is only guaranteed if $E_c(nT) > E_{GOOD}$ counts for all n. Besides, it does not take the limits of the capacitor into account. Therefore a second equation considers the probability that the round itself harvested enough energy, plus the probability that the previous round harvested the missing difference in energy in this round. This is given by (4.20). The formula takes the probability calculation of having harvested sufficient energy in the round itself, and adds an integration over the probability of missing energy in this round which, is surplus in the previous round.

$$\begin{aligned} P(E_c(nT) > E_{GOOD}) = &(1 - F_{E_H(T)}(\mu)) \\ &+ \int_0^{\mu} ((F_{E_H(T)}(\mu) - F_{E_H(T)}(\mu - \tau)) \cdot (1 - F_{E_H(T)}(\mu + \tau)))d\tau \end{aligned} \quad (4.20)$$

Chapter 5

Physical Layer: Wake-Up Receiver

As stated in Section 2.2, wireless communication is the most energy consuming part of the system. Active polling of the radio channel to check if there is an incoming message requires a significant continuous power consumption. In this chapter an ultra-low power wake up receiver (WURx) is described which consumes 1 μW in continuous operation and less than 1 mW during decoding. This WURx harvests the energy in the transmissions of other nodes. If the transmitter uses a varying signal, the pattern that is in the signal contains the transmitted data and is read by the WURx. Comparison of the WURx is made to an active radio receiver and to a WURx that is used to wake up the active receiver.

5.1 Data Transmission

The nodes transmit data using On-Off Keying (OOK). Bits are represented by either transmitting power, for a '1' bit, or not transmitting power, for a '0' bit. Transmission occurs at the transmitting frequency f_{OOK}. The Industrial, Scientific and Medical (ISM) frequency of 433 MHz is selected as transmission frequency instead of the 868 MHz and 2.4 GHz frequencies as it has smaller power decay over distance. Transmitting in this ISM frequencies is allowed by the frequency regulations. A second reason to use 433 MHz is that the RF energy harvesting is done in the 900 MHz band with a broad bandwidth, and a communication frequency of 433MHz has less interference than the 868 MHz band. This is necessary when filters are not ideal. The CC1310 chip consumes 11 mA while transmitting OOK at 10 dBm. Transmission time determines the total energy consumption where a faster bitrate means less consumed energy. A transmitted message adds a preamble before its data frame to let the receiver synchronize to the transmitted bits. This is necessary to correctly read out the bits when they are stable and not in transition. Preamble time should be independent from bitrate, and should be long enough for bit synchronisation. With the WURx, the MCU is in shutdown in normal operation, and is woken up when it detects a transmission. Wake-up time for the CC1310 from shutdown is 1 ms. WURx has to stabilize its readout, and an ADC measurement is done

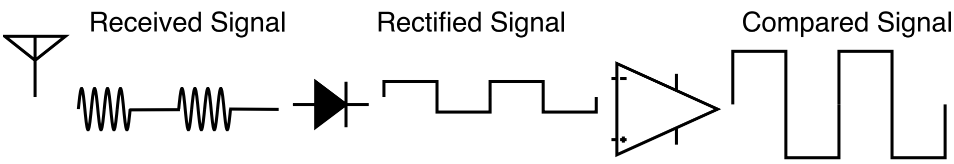


Figure 5.1: **Receiver Overview with corresponding signals.**

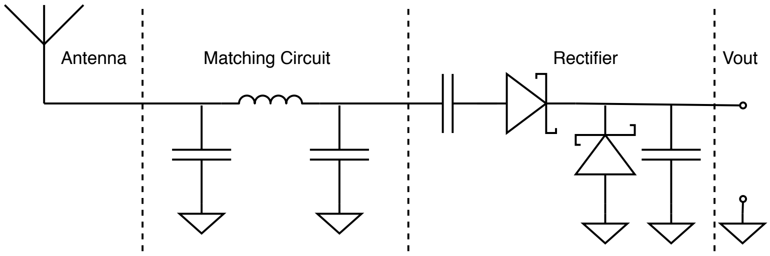
to check link quality. To give the WURx enough time to correctly synchronize to the bit sequence, the preamble time is set to 4 ms.

5.2 Wake-Up Receiver

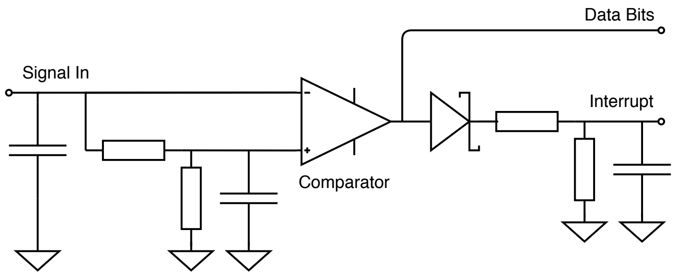
The receiver has to be matched to the same frequency as the transmitted signal. The AC signal has to be rectified to a DC signal in order to let the MCU read the signal. This DC signal has a low value for reasonable distances. A comparator is used to check whether the signal is above a certain threshold. Output of the comparator has the same voltage level as the MCU. In Figure 5.1 it is visualized how the signal is received and transformed to a signal which can be read by the MCU.

5.2.1 Circuit

The data detector circuit is given in Figure 5.2. The data detector uses the same circuit as the RF Energy Harvester circuit in Section 4.1.2 to harvest the signal and get a DC voltage. Compared to the RF energy harvester, this circuit has a narrow bandwidth. This narrow bandwidth will make sure that transmission are only detected at the correct frequency and that messages at other frequencies are ignored. An advantage of a narrowband matching circuit for rectification is that it has a high Q factor which increases voltage. This increase in voltage gain increases the detector sensitivity. Since transmission is OOK, the output of the harvester will be a toggling DC voltage pattern. The RF harvester does not need to power the system so no boost converter is connected to this harvester. However, voltage still needs to be at a certain level to be detected by the MCU. A comparator can detect the difference between the two voltage levels, and output a high voltage for the MCU. To let the comparator know around which voltage to toggle, a low pass filter is connecting the input signal to the negative terminal of the comparator. The negative terminal will get a mean voltage over time between 0 V and the level corresponding to '1' bit. A low pass filter at the output of the comparator will prevent that short noise signals wake up the MCU, and generates an interrupt signal to the MCU. Therefore this signal indicates an ongoing transmission, and will be used to do clear channel assessment. The output of the comparator itself is the data pattern. The interrupt signal is slowly discharged, thus a node does not transmit immediately after receiving the message. This is done to give all the nodes time to process the arrived data and for the WURx to discharge its pre-comparator filter. The only active component in this circuit is the comparator. When there is no transmission, the MCU is in shutdown state. The functioning of circuit is visualized in the simulation of the circuit given in Figure5.3.



(a) **RF harvesting circuit. Transforming input signal to a DC signal.**



(b) **Data Detector Circuit.** V_{out} **is connected to Signal In. Output voltage level can be read by MCU.**

Figure 5.2: **Circuit design for the WURx. .**

5.2.2 MCU Software

An Interrupt Service Routine (ISR) of the MCU is triggered when the interrupt signal becomes high. This ISR will wake up the MCU. The MCU will synchronize between the preambling bits, and will start a timer at the bitrate frequency. Synchronisation is done by checking the preamble signal to see if the timing of the bits is within a limit from the expected bit times. When this bit timing corresponds to the bitrate, the timer is initialized and started at zero halfway the bits. Now the timer will run an ISR halfway each bit. If no preamble is detected, the readout will be canceled. If a preamble is found, the link layer as explained in Chapter 6 will do the byte synchronisation and read the message. The readout will run as long as the link layer indicates or till it times out at a maximum length. In Figure 5.4 the corresponding signals of receiving data are plotted showing the interrupt signal, the data signal, and a debug signal that indicates when the bits are read.

5.2.3 Limitations

Biggest advantage of this WURx setup is the ultra-low consumption. This comes, however, at the cost of a limitation in distance and speed.

Distance

The rectifier outputs a voltage corresponding to the input power. The bigger the distance between transmitter and receiver, the lower the voltage output of the rectifier. With a comparator that is able to see the difference in extremely low voltages, high distance ranges could be achieved. However, the signal to

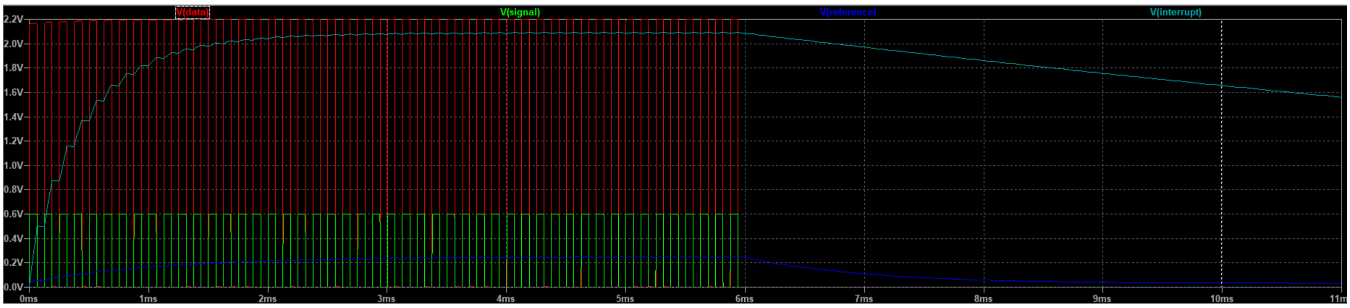


Figure 5.3: **Simulation of WURx circuit. Green = signal, Blue = reference signal, Red = comparator output, Lightblue = Interrupt signal**

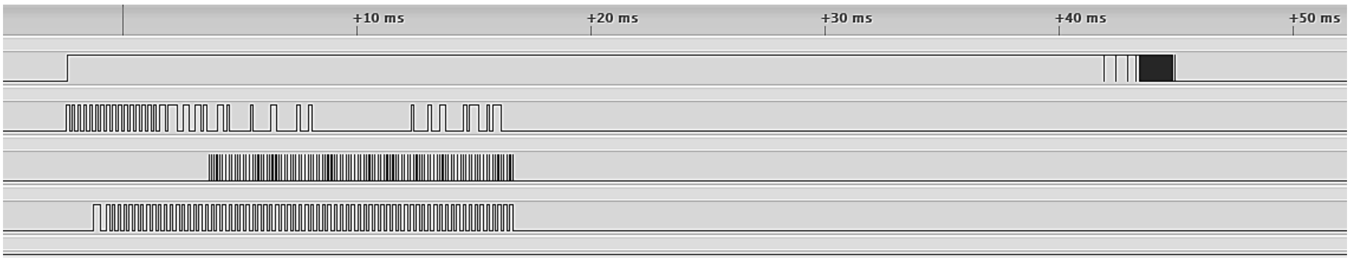
environmental noise ratio would grow. In practice, the comparator is non ideal, and the input voltage must be a few mV. The influence of environmental noise is now limited, which is an advantage, but the communication range is limited as well, which is a disadvantage. More accurate comparators exist, but these have an increase in power consumption. The TSS881 comparator is selected, which runs typically at 200 nA, has 1 mV input offset, and 2.4 mV hysteresis. Because the threshold for the comparator is set halfway the input voltage of a positive bit, the sensitivity is twice the hysteresis level which becomes 4.8 mV.

Speed

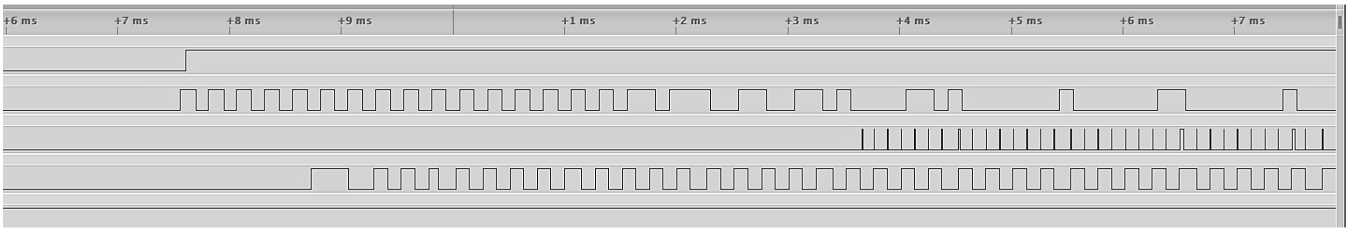
Bitrate is limited by the speed the MCU can accurately read out bits, and by the switching limitation of the detector and comparator. Yet, the MCU runs at 48MHz, and if ISR is kept short, high bitrates could still be achieved. Besides, when the bitrate approaches the limit of the MCU, putting the MCU to sleep is unnecessary, and only results in a delay for waking up the MCU from sleep. The comparator has a propagation delay of 2 μs. This limits the bitrate to 500 KHz, which is still considered as a fast bitrate. Limitation of speed, due to the comparator and the MCU, is at a high bitrate. However, the sensitivity, where the bits are read out correctly, decreases with increasing bitrate. This is due to the harvesting circuit. For the rectifier, the voltage is smaller after rectification as is has smaller time to build up energy for its voltage doubling circuit. This is limited by the capacitance of the schottky diodes. The bitrate determines the maximum sensitivity of the WURx. To achieve a reasonable sensitivity and thereby distance, bitrate should be determined accordingly what is preferred.

5.3 Results

The sensitivity of the circuit is measured using a signal generator. In Figure 5.5 the input power is plotted against the bitrate. As expected, the sensitivity decreases with increasing bitrate. With a starting bit that transmits a high value for > 2 ms, the signal is detected till an input power of -40 dBm, but bit readout is mostly incorrect. In Table 5.1, the theoretical and practical distance with respect to transmission power are given. The bitrate is chosen to be 8 KHz,



(a) **Message Reception.**



(b) **Preamble Syncing.**

Figure 5.4: **Plot of data receiving. Line 1: Interrupt Signal; Line 2: Data Signal; Line 3: Actual Data Readout; Line 4: Bit Readout with Syncing.**

	Theoretical Distance	Practical Distance	Max Achieved Distance	Active Receiver Distance
0 dBm	5 m	+/- 2 m	2.6 m	+/- 25 m
5 dBm	9 m	+/- 4 m	5.3 m	+/- 50 m
10 dBm	17 m	+/- 8 m	10.4 m	+/- 100 m

Table 5.1: **Table with global distances, based on 1 dBm antenna. Sensitivity of -38 dBm. Communication range dependent on LOS and RF environment.**

as good balance point between sensitivity and energy consumption. At 8 KHz, each byte takes 1 ms to transmit. The WURx is tested, and it is seen that it can wake up on incoming messages and synchronize to the bitrate. The link layer should take care of correct readout of data.

5.4 Comparison

The WURx is an ultra-low power solution with limited communication range and bitrate. It is compared to an active CC1310 receiver and to a wake up circuit that wakens a CC1310. This comparison is given in Table 5.2. As explained the biggest, disadvantage of the WURx is in the distance and bitrate. The biggest advantage is in power consumption. If an active receiver would be used, the transmission could be done at lower transmission power and a faster bitrate, which saves energy. However, the continuous energy consumption of the active receiver would quickly draw more power. The WURx solution shifts the energy use to a single transmission, and as a result the node get the ability

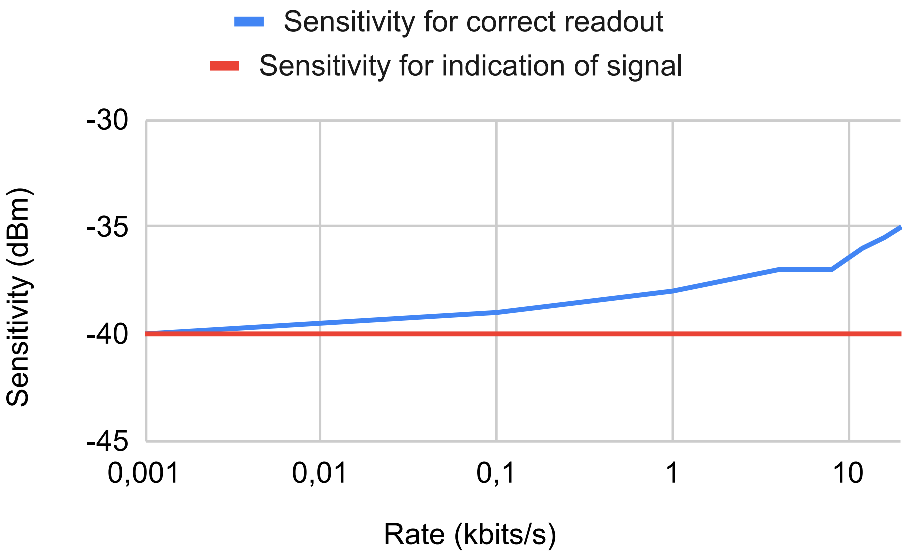


Figure 5.5: **Sensitivity vs bitrate for WURx circuit.**

	Active CC1310	WURx	Wake-Up circuit + Active CC1310
10 dBm Transmitter	up to 100 m	+/- 8 m	+/- 10 m
0 dBm Transmitter	up to 25 m	+/- 2 m	+/- 2.5 m
Bitrate (max)	50 kHz (500 kHz)	8 kHz (20 kHz)	4 ms Preamble + 50 kHz (500 kHz)
Technique	OOK,FSK	OOK	OOK Preamble + FSK Transmission
Power Usage	15 mW	2 μW + <1 mW during readout	2 μW + 15 mW during readout
Advantage	Bitrate, Range	ultra-low Power, Parallel Transmission	bitrate, Continuous Power

Table 5.2: **Comparison of the WURx with an active CC1310 Receiver and with a combination of both.**

to continuously listen. Signal to noise ratio is low at short distances, and the readout with the WURx was proven to be a reliable communication link. More on this is explained in Chapter 6. The active receiver with higher bitrate turned out to be less reliable with OOK transmission. The active receiver needs a precise synchronisation, and the signal to noise ratio for lower transmission power is lower. Hence, this link was tested less reliable. Active communication with FSK is tested as more reliable than OOK. Comparing the WURx with the combination setup, where the wake up circuit starts the CC1310 receiver, gives a slightly higher communication range for waking up the active receiver as an indication of the signal, and not a correct readout, is enough to wake up the active receiver. Readout of the data-bits is done by an Interrupt Service Routine which consume only a small part of the bit time. The other time, the MCU is at standby, and as a result, power usage during readout with the WURx is significantly lower than the active readout. However bitrate could be increased

with an active receiver. Therefore waking up an active receiver will consume less energy if the messages are longer. Likewise, the WURx will be less energy consuming if the messages are kept short.
Nodes have one transmission in each gathering round, but will have several receptions. Hence, the WURx is chosen to receive transmissions. This will result in only a big energy consumption in one transmission. Other advantages are that the transmissions can run in parallel and that Collision Avoidance is performed on limited range with the WURx and that the hidden node can prevented, which will be explained in Chapter 6.

Chapter 6

Link Layer: Collision Avoidance

Medium Access Control (MAC) is necessary to get exclusive access to the communication channel. The link layer in the OSI model takes care of this part. As stated in Section 2.2.4, collisions can hardly be detected in wireless links, and therefore collision avoidance is mainly used in these links to prevent collisions. Additionally, the limitation in this network of EH powered nodes is that nodes have sufficient energy to do one transmission in a time period T. If collisions would have been detected, the node has no energy to transmit a message again. Therefore collision avoidance is necessary for reliable communication between nodes.

6.1 Overview

Carrier Sense Multiple Access (CSMA) is explained in Section 2.2.4 and is used to have multiple devices accessing the same channel. When a node has a message to transmit, it will sense the medium for a current transmission. If the medium is idle it will start a transmission. If an ongoing transmission is detected, the node will backoff for a random time period and when this timer period expires, it will try again to transmit by first listening to the channel. This backoff period gives raise to a delay and a non optimal use of the medium. Decreasing the delay could be done by listening until the channel becomes idle and transmit with a certain probability afterwards. This method is called p-persistent CSMA and is used in example WiFi for example. However if multiple nodes have a pending message to transmit and wait for an idle channel, collisions can occur when they transmit at the same time afterwards. Because the nodes all can transmit once, a collision is expensive, and because they transmit once in a relatively long time period, arrival rate is low. Hence, Non-Persistent CSMA is used to avoid collisions as much as possible. Non-Persistent CSMA does always backoff a random time when the channel is not free. To keep delay short, backing off period is chosen to be a random value between 50-150ms. Now probability is small that within the same ongoing transmission the channel is sensed again meanwhile keeping the probability low that different nodes select the same backoff period. Given the receiving circuitry from the physical layer, see Section 5.2, the inter-

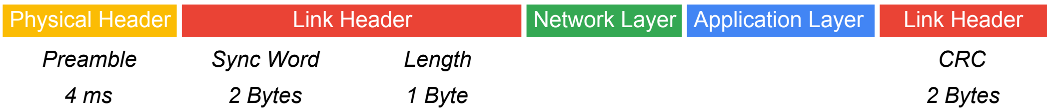


Figure 6.1: **Message Packet Index.**

rupt signal is high during a transmission from a node that is within communication range. If this signal is low, a clear channel is indicated. The data signal itself is sensed as well because the interrupt signal is slightly delayed from the data signal itself. This prevents unnecessary wakeups from noise signal, but can indicate a clear channel during transmission of the first bits.
The decision from a node to transmit, will follow from data in a message they receive from another node. Because other nodes can receive the same message and can have the same decision to transmit, the problem could occur that this transmission will happen at the same time. This comes from the fact that the different nodes run the same code on comparable hardware. The time it takes to process is likely to be the same among boards and probability of collision is high. Even with sensing the medium, the small time between sensing the medium and the actual start of the transmit can still give raise to transmitting at the same time when their processing times are the same. To prevent this, a node always performs an additional random backoff, when the message is created, before transmitting.

6.2 Data Frame

The physical layer was responsible for the bit synchronisation and a preamble is added to synchronise these bits. In the link layer, a SYNC word is added to synchronize the bit sequence to data bytes. A minimal SYNC word of 2 bytes is required by the CC1310 to work correctly. The length of the messages is not fixed and depends on data payload. Hence, a length field is added to the frame. The frame is ended with two bytes of CRC check to check the correctness of the message, see Section 2.2.4. The packet mapping is shown in Figure 6.1.

6.3 Hidden Node

CSMA/CA is lacking the ability of detecting a hidden node. The hidden node problem occurs when two nodes cannot detect other but a node in the middle can detect both. If one of them is transmitting, the other will not sense this transmission and can start a transmission as well. The receiver in the middle cannot receive the messages correctly as a collision will occur. In WiFi and other wireless link layers this problem is solved by using a Request-To-Send and a Clear-To-Send message. These are short messages, that decrease the change of a collision and gives one node exclusively access to transmit the full message [40]. Clearly this is not applicable to this network of EH powered nodes, due to the multiple messages the nodes would need to transmit.

The limitation of the receiving distance of the passive radio was given by the minimal voltage that the comparator of the data detector circuit needed, see

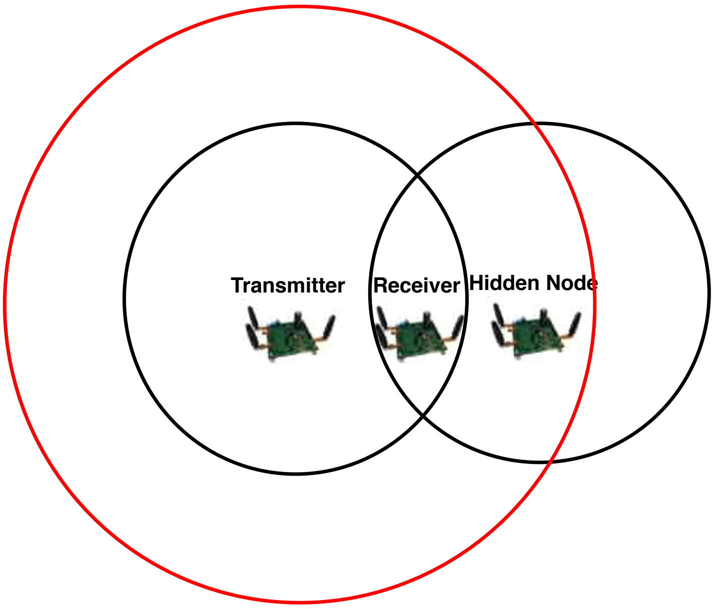


Figure 6.2: **Visualisation of Hidden Node problem and the solution by shortly increasing receiving distance.**

section 5.2.3. The advantage of this limitation is that transmissions that occur at the same time but on a certain distance from each other will not collide at the receiver. To detect larger distances with the radio, the voltage needs to be amplified, which is not done in data reception to save the continuous power consumption that this would require. However, this amplification would lead to doubling the distance and solving the hidden node problem if it would be used at the moment of clear channel assessment. The power increase would be limited to the small moment of clear channel assessment. A visualisation is given in Figure 6.2

6.4 Throughput and Delay

Message transmission is fixed at 1 transmission each data collection round. Hence, total throughput is limited to the number of nodes and the length of the interval between data collection rounds. However, the arrival rate is non random. If 1 node wants to transmit, other nodes are very likely to transmit as well, because of the time correlation. The delay between transmissions is important because the overall goal is time correlation between measurements and therefore short delays are important. In a network of size N, worst case scenario is when a node has all the other nodes in its range and they all transmit each time the backoff of the worst case node expires. Worst case delay is given in (6.1). The additional +1 is due to the initial backing off . Because all nodes can see each other, this is the worst case delay from beginning to end in th entire network. The worst case delay in a line network, where each node has two neighbours and each node depends on its previous node, is still $N \cdot MaxBackoff$ due to the initial backoff before each transmission.

$$MaxDelay = (N + 1) \cdot MaxBackoff \tag{6.1}$$

6.5 Implementation

Amplifying the input voltage is done by an Operational Amplifier (opamp). The chosen opamp is the Analog MAX9114 which needs a current of 20 μA. If the amplification is done only during clear channel assessment this consumes less than 0.1 μJ additional power for a clear channel assessment time of 1 ms. The input of the comparator of the circuit now needs to be toggled, on runtime, between rectifier output and opamp output. Therefore, an ultra-low power switch is added as well. The Analog ADG701 is chosen for its ultra-low power and will consume 5 nA additional continuously power when the WURx receiver is on.

6.5.1 Amplification

To double the detection range, the input threshold of the WURx needs to be 6 dB more sensitive. The 6 dB is because doubling the distance of an RF signal quarters its power, see Section 2.1.2. With the minimal given input sensitivity of -40 dBm, this means that an input signal with power of -46 dBm should be seen as -40 dBm, so the comparator will detect it. A non-inverting opamp setup is chosen and the amplification factor is set by two resistors. Power is quadratic to voltage amplification. Hence, to increase the power with a factor of 4, the voltage should be amplified with $\sqrt{4} = 2$. However, the lower input power has a lower efficiency through the rectifier. Measuring the voltage difference between -40 dBm and -46 dBm is slightly below a factor of 3. The power decay over distance is non ideal as well and therefore to be sure no transmissions can interfere, an amplification factor of 4 is chosen to detect messages far enough. Higher amplification factor is unnecessary and would only give raise to unnecessary backoffs.

6.5.2 Receiving Amplification

The amplification is not used in sleep mode for receiving packets because it would continuously draw significantly more power. However, switching on this receiver when a wake up call is given can increase range and stability a bit. The measured threshold power input levels are given in Figure 6.3. It seen seen that for increasing datarate, sensitivity decreases while assuring correct readout of the data bits. However the detection of the signal is the same for the different datarate if the preamble starts with a long positive bit. When during the preamble the signal is detected and the opamp is turned on, the signal can be read out correctly with a sensitivity of -40dBm. This can be seen in the Figure as the datarate line with opamp turned on is below this threshold level. The preamble of the transmitted message should start with a line of '1's instead of changing bits, to let the receiver wake up at the lowest sensitivity level. This will not increase preamble length, because it can be done in the part that the MCU is starting and the ADC measurements are done. Hereafter, the preamble can be a switching bit signal again for the bit synchronisation.

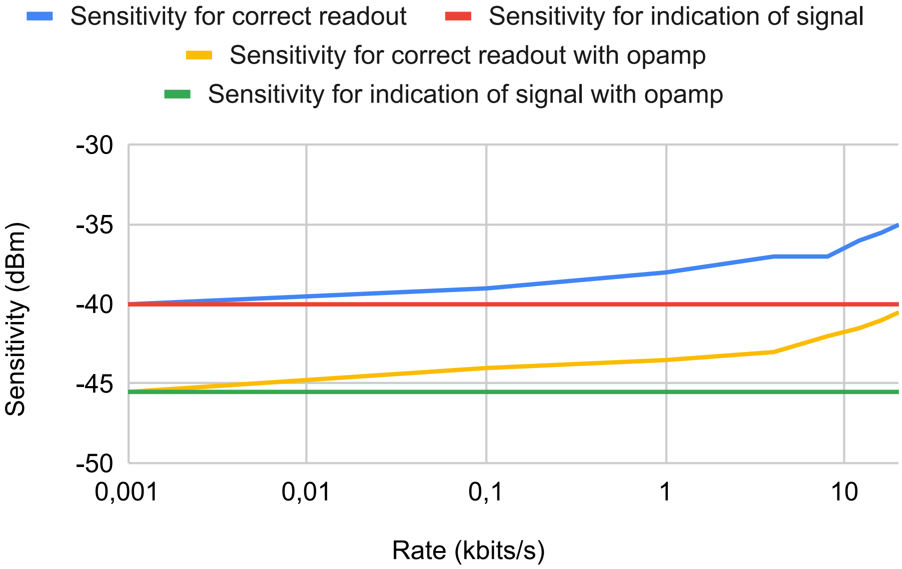


Figure 6.3: **Increased sensitivity, when using opamp for Clear Channel Assessment.**

Figure 6.4: **Analysis of two nodes trying to send shortly after each other with collision avoidance. Nodes do not immediately send after each other.**

6.6 Results

In Figure 6.4, signal analysis of two nodes that try to send shortly after each other is shown. It can be seen that collisions are avoided as the nodes send after each other and it is seen that they backoff when they detect a message. In Figure 6.5, the serial debug output of one of these nodes is given and it shows that it received 6009 packets correctly from node 9 out of the 6223 packets that node 9 transmitted. which results in 96.6 %

To test the arrival rate, nodes count the number of their transmissions. They transmit this number within its message. The receiving node counts the number of receptions from a node and compares this value to the value it receives from the other node. To test the result of the collision avoidance, the test is run with and without collision avoidance and with and without the addition of the amplifier for the hidden node. Test scenarios and results are given in Table 6.1. All following test cases are repeated 10 times, with at least 1000 messages transmitted. First a direct link within communication range is tested with 2 nodes,

```
LinkToBoard (CONNECTED)
[RX]ID:9;R:6205;5991;52;0;      [TX]C:2;B:103;
[RX]ID:9;R:6206;5992;52;0;      [TX]C:2;B:90;
[RX]ID:9;R:6207;5993;52;0;      [TX]C:2;B:134;
[RX]ID:9;R:6208;5994;52;0;
[RX]ID:9;R:6209;5995;52;0;      [TX]C:3;B:80;
[RX]ID:9;R:6210;5996;52;0;      [TX]C:2;B:73;
[RX]ID:9;R:6211;5997;52;0;      [TX]C:2;B:126;
[RX]ID:9;R:6212;5998;52;0;      [TX]C:2;B:138;   [TX]C:1;B:60;
[RX]ID:9;R:6213;5999;52;0;      [TX]C:2;B:63;
[RX]ID:9;R:6214;6000;52;0;
[RX]ID:9;R:6215;6001;52;0;      [TX]C:3;B:75;
[RX]ID:9;R:6216;6002;52;0;
[RX]ID:9;R:6217;6003;52;0;      [TX]C:3;B:110;
[RX]ID:9;R:6218;6004;52;0;      [TX]C:2;B:108;
[RX]ID:9;R:6219;6005;52;0;      [TX]C:2;B:63;    [TX]C:1;B:71;
[RX]ID:9;R:6220;6006;52;0;      [TX]C:2;B:118;
[RX]ID:9;R:6221;6007;52;0;      [TX]C:2;B:64;
[RX]ID:9;R:6222;6008;52;0;
[RX]ID:9;R:6223;6009;52;0;      [TX]C:3;B:64;    [TX]C:1;B:52;
```

Figure 6.5: **Serial Output of one node. It received 6009 out of 6223 messages from node 9. For each transmission, the number of backoffs and the last backoff time is given.**

one transmitting and including number of total transmissions. The receiver shows the amount of correct received messages. There are no other nodes transmitting and therefore the expected correct arrival value would in theory be 100 %. It is expected to be slightly below that in practice, due to noise in RF environment, or other unknown sources transmitting thereby creating bit errors. However in most tests that were run with nodes close to each other, all messages arrived for 100 %. Placing the nodes above 75% of the communication range, some packets were missing but the link kept 99 % correct arrival rate. The probability is not much dependent on distance, only at maximum range this rapidly decreases. Probability was expected to decrease more over distance, but the -40 dBm is in RF environments significantly above noise level.
In the second test, 2 nodes are trying to transmit messages. After transmission they immediately queue a new message with a random initial backoff time. This initial backoff time is a random value between 50 ms to 150 ms. Message length is 20 bytes including preamble and headers. Transmission is at a bitrate of 8KHz and therefore, transmission takes 20 ms. The messages should not overlap in order to not collide with each other. The expected value over time of the backoff time is 100ms and therefore the probability of correct arrival rate is $1 - \frac{2 \cdot 20\,ms}{20\,ms + 120\,ms} = 66.7\,\%$. For 3 nodes to not overlap this becomes 50 %. Running the test gave an average of 73 % correct arrived messages for 2 nodes, and 45 % correct arrived messages for 3 nodes.
The two nodes setup turned out to be slightly higher than expected. There is a small delay between ending a transmission and setting the backoff for the next transmission. As well there is a small delay after a backoff ended and the transmission is started. This can be the reason for the small increase in arrival rate, because time between messages is slightly higher. The explanation for the 3 nodes setup to drop below expectation is that the messages are not transmitted in bounded timeslots. Hence, two messages that are transmitted within $< 20ms$ from each other prevent, the third node of falling between. This decreases the

	Expected Value	Measured Value
Single Link	99%	99%
No Collision Avoidance 2 Nodes	66.7 %	75 %
No Collision Avoidance 3 Nodes	50 %	45 %
Collision Avoidance 2 Nodes	99 %	97 %
Collision Avoidance Hidden Node	66.7 %	75 %
Collision Avoidance With Amplification Hidden Node	99 %	94 %

Table 6.1: **Expected and measured values for different test cases.**

probability of correct arrival for 3 nodes.
In the third test, the collision avoidance is used. Nodes are placed in range of each other. The test gave an average arrival rate of 96 %. The time between sensing the channel and the actual transmission turned out to be 2 ms. This is because the radio core of the CC1310 MCU is turned down in sleep and started after sensing the medium, to prevent unnecessary wake ups. However, this 2 ms on an expected backoff of 100 ms and a transmission time of 2 ms, give a change of 2/120 = 1.67 % that the other node start a transmission as well. This time delay is improved by performing an additional check after starting the radio core to see if the channel is still idle and the time delay is decreased to 250 μs, which give a change of 0.25/120 = 0.2 % of collision in this time span. An unnecessary wake up of the radio could be made, but this one is powered down if not yet needed and collisions need to be avoided as much as possible. This improvement gives an arrival rate of 97.5 %. The difference in between this values is as expected. However, there is still a probability of 2.5 % that collisions occur when transmitting under these conditions, which is higher than is expected for the time delay between sensing and the start of the transmission. It has been made sure that the nodes are within range, so the reason for this few collisions has to be originating from some other part. The radio transmission from a node charges its own WURx because in the implementation the receiving and transmitting part use their own circuitry and antenna. These antennas are close to each other and WURx gets charged to a high level. During transmission, the interrupt for radio reception is turned off, so the node do not try to read its own message, After transmitting, the radio has to power down, interrupt is turned on and MCU has to turn down. If the other node tries to transmit now, it will see a clear channel, but the node that just transmitted might not be ready yet and its filter before the comparator in the WURx is charged higher than a positive '1' from an other node and will miss the syncing in the preamble. In the results is seen that most missed message give wrong synchronisation or CRC fault, so bit readout is incorrect. It is tried to prevent this by slowly discharging the interrupt signal so that other nodes do not immediately transmit after another message. But in the small collision rate it is seen that in a few cases, a receiver is not ready to receive.

For the tests with the hidden node, first the sensitivity with the amplification is tested, to show case correct result. Result is given in Figure 6.3. It can be seen that sensitivity is increased with the 6 dB as calculated. As well it can be seen that message reception at the chosen datarate of 8 KHz with opamp turned on is below the detection threshold with opamp turned off. Hence, turning on the opamp after the wake up for a reception, increases reception sensitivity towards this level.
The tests with the hidden node, are done with collision avoidance turned on. The setup is with 3 nodes placed as given in Figure 6.2. Without amplification, the results are the same as with collision avoidance off, and the nodes placed within range. This is as expected because the nodes out of range cannot reach each other and do not backoff again. The test with the amplification turned on shows that this solution for the hidden node problem works, now correct arrival rate at the node in the middle is increased to 94 %. This is slightly lower than with the collision avoidance in range. With the amplification, more noise is amplified as well, and it is observed with an oscilloscope that bit edges are less sharp. This can originates from the added capacitance in the circuit due to the amplification. These effects are small, but give raise to the small decrease in arrival rate for nodes at this distance from each other. This decrease does not occur when using the amplification for nodes closer to each other because the received input power is higher.

From the results in 6.1 can be seen that with introducing collision avoidance, message reception is much more reliable. As shown, the introduction of the amplifier limits the hidden node problem. Although, within hidden node ranges, the collision rate is a bit higher. As difference between single link transmission and multiple link transmission the reception probability decreases from 99 % to 97 %.

Chapter 7

Network Layer: Multi-Path Algorithm

This chapter describes the algorithm that collects measurement data of all nodes in a network of energy harvesting nodes. The algorithm is part of the network layer. The nodes in the network can transmit one message and they all want to report their data. In graph theory terms, a tree with leafs ending in different nodes would be created if each node broadcasts a message after if it is awakened by an incoming message. Therefore, the algorithm finds a gateway oriented Directed Acyclic Graph (DAG) of the network, starting in a special source node and letting all leafs end in the gateway. Within the model of the transmission layers, the network layer assumes that the link and physical layer take care of the correct arrival of messages.

7.1 Overview

Due to the energy constraints, it is given that all the nodes can transmit once in time T. T is given by the minimum time that the node needs to charge to have enough energy for a transmission and processing of data. Taking this time for the node that harvests the least amount of energy results in a certain probability, described in Section 4.4.1, that all nodes are awake after this time. The algorithm is divided in data collection rounds with each round separated in time with T.

In Section 3.1.5 it is described that the network has a gateway to collect all data. Further, it is given that for bigger networks, data needs to hop through the network. One node, preferable the one the furthest away, is selected as a special node within the network. This node can start transmission rounds. The idea behind choosing the node the furthest away is that this gives the minimal amount of hopping over nodes if all nodes need to be reached. It does not need to hop away from the gateway first and than hop back. When the network is RF powered, and the gateway is placed closest to the RF source, than this special node is as well furthest away from the RF source and therefore, if this node has sufficient power, all nodes do. Theoretically, this node furthest harvests the least amount of energy. However, this is strongly influenced by the RF environment.

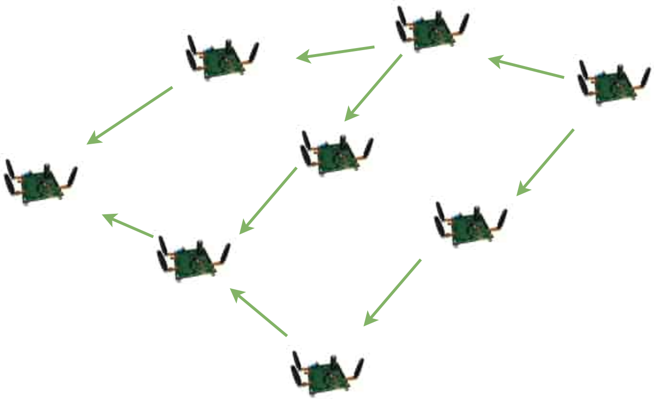


Figure 7.1: **Network overview: Green arrows display incoming links that nodes need to receive before transmitting.**

The special node, called the source node, starts transmitting a message after time T. This message hops over all possible paths to the gateway. If this message hops over all paths it will reach all nodes. If all nodes would broadcast the message they receive, the message will get stuck at multiple nodes as, in graph terms, a tree is formed. The shortest path from source node to gateway will reach the gateway but other paths would rely on other nodes transmitting twice. However, if certain nodes would wait for incoming side paths, all data measurements can be gathered at the gateway with each node transmitting once. Therefore, all nodes need to know their important incoming links. If they know these links, they can wait for a message from all these incoming links before transmitting. In Figure 7.1 such a network is given with the green arrows displaying all important links. The proposed algorithm generates a set of incoming links for all nodes.
The placement of the nodes in the network is limited to the requirement in Theorem 1. This is visually shown by the network in Figure 7.2. The node in the circle cannot transmit twice. This node is in both 1-vertex-connectivity sets of the two lower nodes. The 1-vertex-connectivity set of node i towards the rest of the network is the set of nodes that when removed make node i unconnected to the network.

Theorem 1 *Let S_i be the set of vertices that makes node$_i$ 1-vertex-connected to the gateway.*
Let T_i be the set of vertices that makes node$_i$ 1-vertex-connected to the source.
For each node$_i$, the intersection of both sets S_i and T_i should be empty.
i.e. $S_i \cap T_i = \emptyset$

If node$_i$ does not meet this condition, node$_i$ can not reach the gateway in the same round through multihop as another node would have to transmit twice.

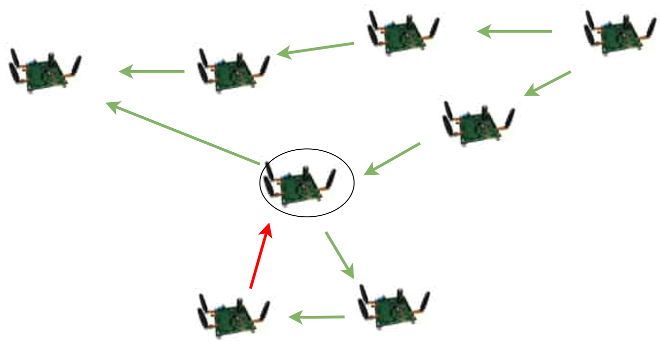


Figure 7.2: **Network requirement: Bottom two nodes cannot reach gateway in same round.**

7.2 Proposed Solution

Exploring Part

The algorithm is started with the exploring part where nodes find their distance to both gateway and source. The first round is started by the source node and an EXPLORING message is broadcasted with hop level '0' indicating distance to source node. Each node can receive this message from all its neighbours. All the nodes take the lowest possible level and increase this level with one. After increasing, they broadcast the message further to the rest of the network. All nodes now know their shortest distance to the source node. The second round is the same as the first round but started from the gateway node instead of the source node. Each node now stores two levels indicating distance to both gateway and source node. Besides, a set of information about the neighbours with their levels is stored. The levels of the neighbours are known as the node receives their messages.

A problem that arises is the causal ordering of messages when nodes broadcast immediately after they receive the EXPLORING message. In theory, a node can receive a lower level from another node which was delayed. It cannot be completely guaranteed that this cannot occur because neighbours are not known and nodes can only transmit one message. However, the probability that this occurs can be made small. By introducing a time delay T_{EXP} before transmitting this is done. After the first arrival of a round, the time delay is started. This delay is a fixed value for all nodes and give the nodes with a lower hop count the time to transmit their message. First arrival between nodes differ in time and therefore this fixed time value will be shifted between nodes. Therefore, this delay should be chosen significantly bigger than the random introduced delay in the link layer. When $T_{EXP} >> T_{LINK}$, the probability that the ordering of hopping messages is correct is high. Data is not gathered in the two exploring rounds, hence, the introduced delay is not a problem.

A second problem arises when a link fails due to bit errors or collisions. The node can get a higher level than it should have had with respect to the available links. It cannot be prevented that this happens. Hence, a solution is needed to correct the errors in the exploring part of the algorithm due to a failing links or a wrong causal ordering. When the graph is still connected, a solution is

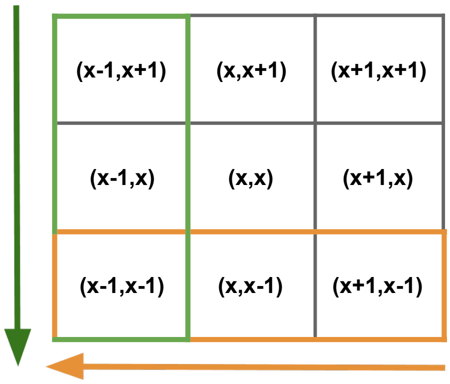


Figure 7.3: **Levels of neighbours in the network with respect to the node. Each neighbour is modeled as 1 of the 9 possible combinations.**

always found based on a network without the missing links. In later rounds, the nodes keep adding their levels in their transmissions so the other node will get to know missing links and update their information. The network can converge to corresponding levels. It can only converge to lower levels and therefore the network stabilizes. Links that have a low link quality, which means they are on maximum communication range, are omitted in the exploring part so they do not form critical links. Nonetheless, messages over these links are still received and during data rounds, they are still read when other links fail.

Resolve Important Links

Next step is to select the important links between nodes with their corresponding direction. The level of a neighbour towards the gateway or the source cannot differ with more than 1 from the node itself. All neighbours of each node are characterized by one off the 9 level combinations given in Figure 7.3. Nodes that meet the requirement given in Section 7.1, have at least one node being in the green set, and one node being in the orange set. Consequently, all these nodes have a set, Ng_i, of neighbours with a lower level to the gateway with size of at least 1. Likewise they have a set, Ns_i, of neighbours with a lower level to the source node with size of at least 1. These two sets can intersect.
To find a solution that minimizes the network delay and minimizes the amount of important links, a node only needs to find one best incoming and one best outgoing link. The incoming link needs to be the shortest path from the source node and the best outgoing link needs to be the shortest path to the gateway. When having multiple neighbours in one of the sets, the best link is chosen in the direction of the arrow. This is to let outgoing and incoming link not interfere with each other and to minimize overall delay. With multiple neighbours having same levels, they could all be chosen as best link. To make a decision, the one with shortest distance is chosen. A note: this gives shortest distance between these nodes but not necessarily shortest distance on overall base.
A problem arises when the best outgoing link is the same as the best incoming link, with level being (-1, -1) with respect to the node itself. Even with multiple neighbours having (-1, -1) no decision can be made that can not result in an

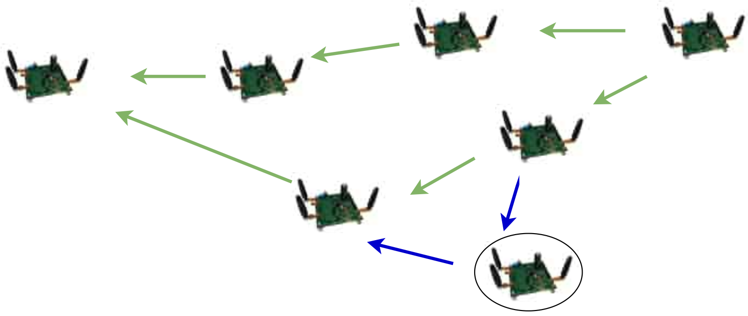


Figure 7.4: **Learning from Neighbours.**

undesired cycle in the graph. If a cycle would be created, the network will get into a deadlocked system during data readout. Therefore these nodes will be left pending. All chosen links form the DAG which starts in the source node and ends in the gateway.

Data Rounds

After these two exploring rounds, at least the shortest path is always found. The source node can start the next data rounds with application layer data included. Every node waits for its incoming links before transmitting. In the transmissions during these rounds, the network layer header of a transmission includes its levels and its decision about best outgoing and incoming link. During these rounds, the nodes learn about the decisions of their neighbours and add their outgoing links to their own set of incoming links. If every node had made a decision after the exploring part, all of the network is known by now. In next data rounds, all data can arrive at the gateway.

Unknown Nodes

When certain nodes did not make a decision yet, they can still broadcast their message after an incoming message and hope it arrives earlier than the transmission at the next node. Meanwhile it keeps checking the other messages that arrive to check if it can make a decision yet. A decision can be made if one of the following occurs:

Neighbours choose: If two neighbours set an incoming and outgoing link to this node, the node can choose those links in the opposite direction. Those links where guaranteed to not form a cycle and can therefore be safely chosen.

One link is set by a neighbour: If a neighbour set an incoming or outgoing link to this node and it has just 1 other link left. It can set this to the opposite link.

Triangularity: If a node has two neighbours and they set a link between them with a certain direction, this node can follow that direction by setting both link. See Figure 7.4.

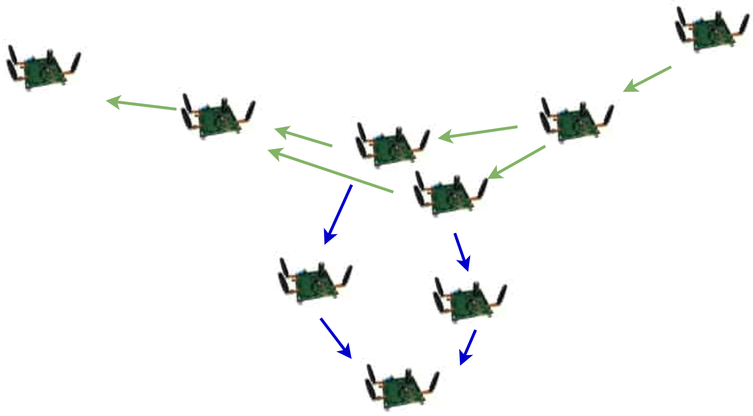


Figure 7.5: **Unsolved Part of the Network.**

If a node is not solved within a current round, perhaps it can be solved in a later round. The biggest part of network will be solved immediately. The small part that remains will converge during next rounds.

Unsolved Nodes

Networks that have the topology as given in Figure 7.5 can occur. Hereby the side path needs to start from a node with levels that are the same as the node where the side path ends. In fact, it does not matter which direction of the path is taken as it will start from a node with identical levels as the node it will end in. In this specific case, choosing a side would result in a correct solution. However, this is not always the case. Suppose there would be a side path at the upper side which would choose the other direction, this would create an incoming link which relies on the outgoing link from that node itself and consequently creates a cycle. Decision cannot be made because it will not definitely create a correct solution. Basically the algorithm sees no difference in both nodes at the start of the sidepaths as they have the same levels and for the nodes in the lower side path they are both closer to gateway and source node. If nodes with the same level would be considered as one node, the requirement in Section 7.1 show that the nodes in the bottom do not meet the requirement. Spreading the nodes and considering a minimal distance in between the nodes, minimizes the situations where this occurs.

7.3 Proof of Algorithm

All chosen outgoing links by the algorithm are directed towards a lower level to gateway. Given two nodes i and j with $LevelGateway(i) < LevelGateway(j)$, direction must be from j towards i or the link is not set as important link. This counts for all i and j in the network and can therefore not create a cycle. The same applies to the set of all chosen incoming links. They can never form a cycle, as they are always directed towards the source. Combining both sets of incoming and outgoing links gives the overall outcome of the algorithm. The combined set cannot form a cycle because for each node i the following applies:

- The link to a neighbour with a level combination of (-1, -1) is not chosen because it could create a cycle. A cycle could be formed because one node can chose the same direction of the link as the other node;
- The link to a neighbour with a level combination of (-1, 0) or (0, -1) can be chosen by this node as incoming or outgoing link, but the other node cannot choose this link. The link follows the direction towards to gateway or towards the source;
- The link to a neighbour with a level combination of (-1, 1) or (1, -1) can be chosen by this node and by the other node as well. However, the other node can only choose it with the opposite direction of this node and therefore it cannot create a cycle;

7.4 Metrics

Networks can have long side paths that give raise to increase in delay due to additional hops and to packet loss. The metric for the added delay with respect to shortest path is given in (7.1). This metric will be $>= 1$.

$$D = \frac{LongestPath}{ShortestPath} \tag{7.1}$$

The linearity of the network is given by the metric in (7.2). This metric will be $>= 1$.

$$L = \frac{NumberofNodes}{ShortestPath} \tag{7.2}$$

In a perfect line network, D=1 and L=1. The network has good parallel side paths when D keeps close to 1 but L increases. This is for example the case in a grid. When D goes above 2, the messages have to hop twice as much as in their shortest path and the algorithm becomes unfeasible.

7.5 Message Arrival

When a transmission round is started, there is small probability that a node is not awake. Furthermore, even with the collision avoidance within the link layer, a message might not arrive due to certain RF interference. If node j within the $>$ 2-vertex-connectivity set of node i is not transmitting, some node in the network will keep waiting for the incoming link from this node j. With introducing a timeout for incoming links, the message propagation will not completely stall. If a node j within the 1-vertex-connectivity set of node i is not transmitting. node i will not be reached through incoming links. But along the path towards this node i there might be a link that is not set as an important link but when a transmission along this path is detected, a node can still be awakened. If no other link is connected towards this node, the node will not be awakened and part of the message propagation stalls.
Because data from the nodes that have previously transmitted is added to the

messages, nodes can see whether they have missed certain links, and this incoming links can be set as received.
The vertex-connectivity sets of a node show the reachability of the node when a node or link within the network fails. If for node i, the 1-vertex connectivity set towards the gateway is empty, it has for all nodes towards the gateway an alternative path. Therefore, the probability is higher that its transmission will reach the gateway. Likewise, if the 1-vertex-connectivity set from the source-node to node i is empty, probability is higher that it is awakened in a data round.

7.6 Results

7.6.1 Simulation

The algorithm is implemented and simulated in Matlab. Using randomized networks as input, correct working is verified. All chosen links form a directed graph and correct working is verified if this graph is acyclic, each node is reachable from the source and each node can reach the gateway.

Input Networks

In Figure 7.6 and Appendix A.1, several different random networks are given with the algorithm run over it. In the Appendix a network of size N=40, a grid network, and two line networks are given. One line network has nodes separated with 3m and the other with 5m. With a communication range of 8 m, the fist line network has stronger connectivity than the second because each node can reach at least 4 other nodes. The line simulation with interdistance of 5 m has a strong changing curve and with this specific simulation, a network where 2 nodes are not taken in the solution is seen.

Verification of Simulation

In Figure 7.6, visual output is shown and working is verified according to the levels of each node and the direction of the edges. The bottom-left graph shows a directed tree which is formed if the nodes would immediate broadcast. The graph in the middle is formed when nodes wait a moment after reception before broadcasting. This way previous nodes are given more change to reach the node. It is clear that these two graph results in different ending leafs of the tree and that the graph is not gateway oriented. Although it is a non cyclic directed graph, data would end at different ends of the network. The bottom-right graph forms a directed acyclic graph with all leafs ending in the node with ID '1' which is the gateway. When all nodes wait for its upper tree incoming leafs, than all data will be gathered at the gateway. The gateway oriented directed acyclic graph of the given input networks verifies correct result of the algorithm. Running the networks with bigger sizes or different shaped field results all in correct behaviour. Because this is unclear from visual inspection, the Matlab simulation can test the formed graph of the links on being acyclic and on the fact of in this DAG, the node with ID '1' is reachable from all other nodes, if this is both true, the result is correct.

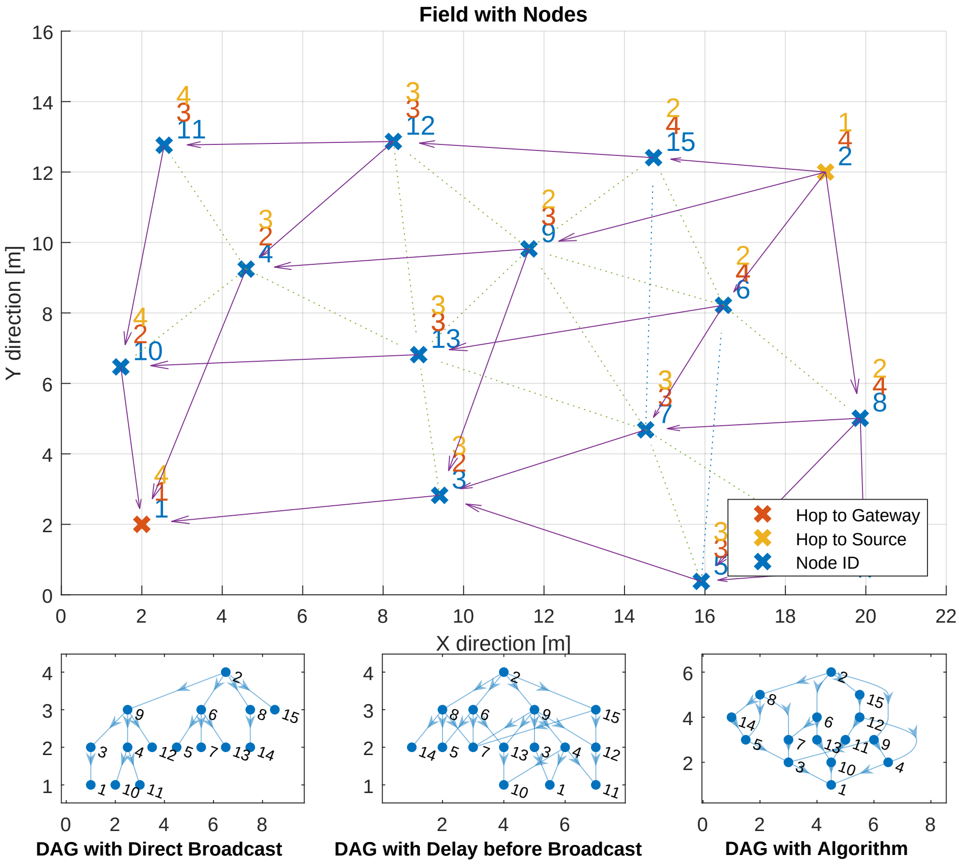


Figure 7.6: **Matlab Simulation of an example network.**

Histogram of Random Networks

Because in certain network topologies, small parts of the network can not be solved, a histogram is given in Figure 7.7 of the percentage that is solved over an amount of 200 different networks over 3 different shaped field of the same area. The randomized network are for N = 25, minimal interdistance = 2 m, Link Distance = 8 m and Field = 15 m by 25 m, 19 m by 19 m and 37.5 m by 10 m. As can be seen, a solution is almost always found and in most of the cases, a solution is found for all nodes. The more linear field of 37.5 m by 10 m results in a few cases where no solution is found which is due to the fact that the random placed nodes are spread over a longer distance and therefore probability is increased that this is more than 8 m away from gateway or source for all nodes, resulting in an unconnected graph. The results are interesting, the 25 m by 15 m field results in more nodes that do not meet the requirement. This can be due to the fact that the more linear network has a limited height which is close to the link interdistance and therefore the probability that the nodes have a link to other nodes on that line is high. However it is not only about having a single link because it should have a second link at least to forward the message and these should lay away a bit from each other. This is more likely

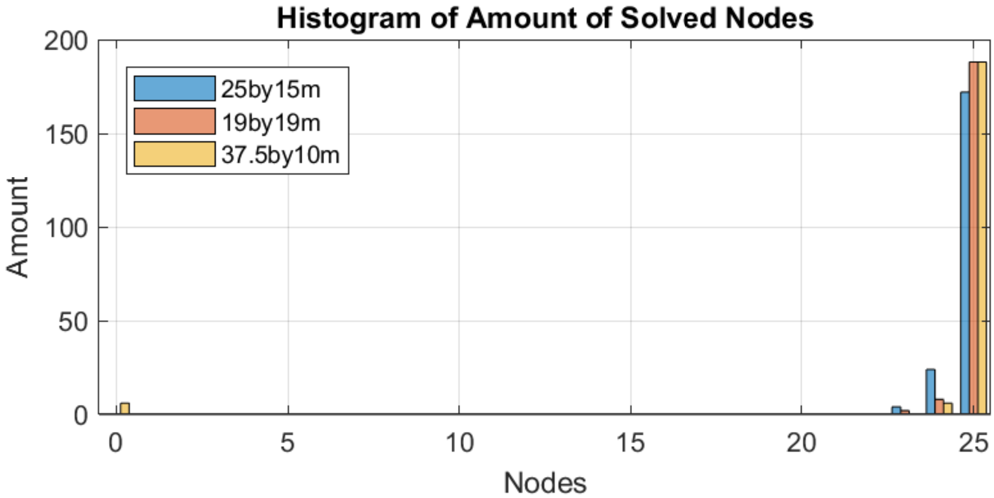


Figure 7.7: **Histogram of 200 random networks for 3 different shaped fields.**

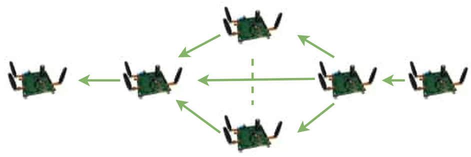
to happen in the squire field where the maximum height and width are both limited to a mean value. In the rectangle 25 m by 15 m field, the probability is higher that a second link is not found for the node to meet the requirement. Therefore probability of few nodes not being taken in the solution is increased a bit. With the mean of these 3 fields, in 92 % all nodes are taken in the solution, in 6 % one node is missing and in 2 % more than one node is missing.

Overall conclusion according to the simulation is that even with random placement and given a connected network, always a solution is found and at most 1 or a few nodes are missing in a low amount of networks.

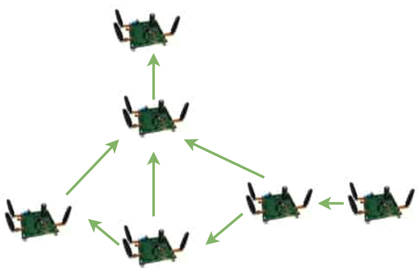
7.6.2 Implementation

The algorithm is tested over several real test setups. Test setups consist of 5 nodes and a gateway. The algorithm is implemented in software and run on the CC1310 SoC. The nodes are checked on having the correct levels corresponding to their location in the network. Their incoming and outgoing links are analyzed to verify correct behaviour. The algorithm is working correctly on the small test setups, and all nodes in the network are part of the found DAG. The strength of the different network setups is tested with the implemented link layer. The algorithm is run and the total percentage of arrived messages is reported. For this part, the nodes are battery powered so the influence of the RF harvesting is not considered for now. Rounds now can have a short time interval to get more data in shorter timespan. All tested networks are run over 5 different runs with each having > 500 rounds. It is noted that the results below are mainly given by the reliability of the link layer. Decreasing collision probability and bit errors in the link layer will increase probability of receiving data during a transmission round. It is observed that multihop decreases the probability of receiving the final messages. Working of the network layer algorithm is demonstrated to be

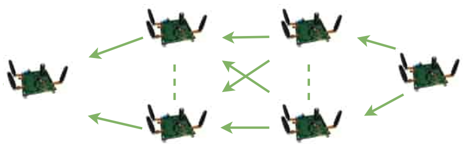
(a) **Test Setup A**



(b) **Test Setup B**



(c) **Test Setup C**



(d) **Test Setup D**

Figure 7.8: **Different Test setup topologies.**

	Number of received measurements					
Test	5	4	3	2	1	Received
A	93,8 %	0,0 %	0,0 %	0,0 %	0,0 %	93,8 %
B	87,0 %	4,2 %	4,0 %	0,0 %	0,0 %	95,2 %
C	94,0 %	1,8 %	1,4 %	0,0 %	0,0 %	97,2 %
D	86,3 %	5,9 %	3,8 %	0,0 %	0,0 %	95,9 %

Table 7.1: **Test results with number of received measurements in percentage of all transmitted rounds.**

correct. However the robustness of the network is based on the probability that links between nodes do not fail, and therefore different network setups are tested.

A: Line Network

The first network that is tested is a perfect line network. It is expected that the arrival rate drops as the length of the network increases. Collisions should not occur because each node depends on its previous node. Message arrival depends on the arrival rate probability of single links. No alternative paths exist, hence, either all data arrives or no data arrives. Total message arrival is tested and the result at the gateway is that 93.8 % of time, all data arrives. With 99 % link arrival probability, this is just slightly below the expected result of 95 % ($0.99^5 = 0.95$) for 5 nodes, .

B: Multipath Network

In test setup B, a multipath setup is tested. If a link in the middle fails, data of other nodes can still arrive. The first and last link are still critical links. Due to the probability that the collision avoidance is not working as expected, there is change that messages collide. The node before the gateway has three important incoming links which is verified in the test case. All other nodes have one incoming link. Total arrival rate is expected to be 97 % ($0.99^3 = 0.97$). Arrival rate of 5 nodes is expected to be 91 % ($0.99^3 \cdot 0.97^2 = 0.91$). The results of 87 % total arrival rate and 95 % that any message arrives is slightly below this expected result. Arrival rate probability of receiving 4 and 3 nodes is both 4 %. Results are slightly below expected values, but the arrival rate that any message arrives is higher than previous setup.

C: Side Path Network

A third setup has a higher D value. The setup longest path and shortest are respectively 5 and 3. The node before the gateway has 3 incoming links again. The nodes are not likely to transmit at the same time because they are dependent on their previous nodes. The probability that 4 messages arrive should be slightly higher than the case that 3 messages arrive because of the additional links this relies on. This is what can be seen in the result but the difference is small. The probability that data arrives is the highest for this test setup, both in receiving any measurement as in receiving all measurements. This is due to the small collision changes.

D: Grid Network

In test setup D, all nodes have >2-vertex-connectivity to all other nodes, including source and gateway nodes. In this setup failure of one of each of the nodes in between does not result in no reception at the gateway. However, with a collision probability of 3 % , the first two nodes and the last two nodes can still collide resulting in no correct arrival at the gateway. It can be seen that results are similar to test setup B but where setup B had an even distribution between 4 and 3 nodes arriving, setup D has more arrival rate probability distributed to 4 nodes arriving because of the higher connectivity of the nodes in the network.

In overall, the arrival rates are slightly below the expected values. This can be due to slightly lower probability of arrival between links in the test environment. With multihop, a small difference in probability is integrated. In the same way, the collision avoidance can behave slightly different under the circumstances. However, the results do not differ much from expected results.

7.7 Conclusion

A network layer algorithm finds a gateway oriented DAG of a network starting in a special source node. Measurement data off all nodes are gathered in rounds and all nodes have to transmit just once in a round. The algorithm is simulated and implemented. It is proofed that the algorithm is working with random networks. With a set of 25 nodes in a simulation of 600 random networks, the solution was found for all nodes in 92 % of the cases and in 6 % just one node is missing. Feasibility and robustness of the algorithm strongly depends on the link layer and the chosen network setup. It is shown on different test setups with 5 nodes, that a message arrival of 95 % is achievable.

Chapter 8

Overall Results

This chapter presents the results of the overall achieved results.

8.1 Timing Periods

A signal generator is used to test a node with a continuous power signal. The signal generator provides a stable input signal. For different input power levels, the minimum timing interval between data collection rounds is tested. The timing intervals are measured as the minimum time that is in between the startups of the node. Results are given in Table 8.1. The node starts when it has sufficient power and waits for the incoming message according to the implemented algorithm. For the different input power levels. With an input level of -12 dBm, 6 μW of power is harvested and a minimal timing period of 12 minutes is obtained. With -14 dBm of input power, slightly above 1 μW is obtained. With this level, the timing period would become an hour, and when the system is started it can barely feed the constant power consumption of the ultra-low power radio. An RF input power of -12 dBm giving 6 μW is chosen as minimal level where the system is feasible. It has to be pointed out that a signal generator gives a steady signal and in real life the input power will be more fluctuating. This is discussed in Section 4.4.1. Therefore timing periods should be chosen higher according to the fluctuation in RF.

8.1.1 RF Interference

Within a range of 1.3 m from the power transmitter at 915 MHz, the WURx, tuned to 433 MHz, was triggered by the RF transmission at 915 MHz. The matching network filter tuned to 433 MHz is a first order filter and the high power of the power transmitter gives a few mV at the WURx, triggering it to start receiving. If communicating nodes are close, reception can still be received because the transmission at 433 MHz overpowers the 915 MHz at the input of the WURx. However, the node cannot transmit because it does not see a clear channel. A stronger filter in the matching should be used to limit this effect. With distance higher than 1.3 m, the WURx was not triggered by the RF power transmission.

Input RF Power	-5 dBm	-8 dBm	-10 dBm	-12 dBm	-14 dBm
Available Power	65 μW	30 μW	15 μW	6 μW	1 μW
Time Interval	1 min	2 min	5 min	12 min	1 hour

Table 8.1: **Timing periods for different input powers.**

	Test Setup 1	Test Setup 2
Time Period	4 min	15 min
Receiving Measurements	100 %	86%
Of 4 Nodes	92 %	86%
Of 3 Nodes	5 %	0 %
Of 2 Nodes	3 %	0 %
Of 1 Node	0 %	0 %

Table 8.2: **Table results of overall test.**

8.2 Test Cases

It is proven that the system works for low input powers. In a concluding test, several nodes are powered by a true RF transmission. The algorithm is run over a set of 4 nodes powered by the 915 MHz RF transmitter. RF transmission power is 30 dBm, and interlink communication distance is limited to 2m to test a network setup. Now a small network with neighbours that can see each other is tested to see if collisions are prevented and if the nodes are awake at the expected time. A note is that on this distance, hopping would not be necessary because the gateway could directly request all nodes. However, it is done to practically test the system and the algorithm. In Section 4.3, it is tested that on a distance of 2m of the RF transmitter, a minimal input power of -8 dBm can be achieved. If the input power would be constant, timing interval could be set to 2 minutes. In the test case timing interval is set to 4 minutes and nodes should always be awake when the data collection round is started.
The results for this test case are given in Table 8.2. Probability that the nodes have sufficient energy after the time interval of 4 minutes is high. According to the test results, still few messages are missing which is due to the link layer. All nodes transmit in parallel and in all cases the data of at least two nodes is collected. Because the probability that all nodes have either a collision, a failing link or are not awake is extremely low, and as can be seen, this does not occur. In 92 % of the cases the measurements of all nodes are collected.

In a second test case, all 4 sensors are placed in a line and hopping is necessary for the nodes to reach the gateway. Sensors are powered through the RF source at a maximum distance of 4m from the RF transmitter with a minimal input power of -12 dBm. Timing interval is set to 15 minutes. Message arrival now depends on all nodes to be awake and no link failing. In this line setup, either all arrive measurements arrive or none of them do. Results are given in Table 8.2. There should be no change of collisions, because each node depends on its previous node. It is tested that in 86 % of the collection rounds, the measurements arrive. This is lower than the test case where nodes transmit in parallel and is due to the dependency on previous nodes. It is lower than expected for a direct link probability of 99 % as is given by the link layer. 95 % ($0.99^5 = 0.95$) would be expected and therefore the remaining measurements that do not arrive are a result of one of the nodes not being awake.

Chapter 9

Conclusions

This thesis proposes a novel algorithm for energy harvesting powered nodes to report their data measurements with correlation in time.

Data collection rounds are started in a special source node and a message is transmitted through the network of energy harvesting nodes. Each node measures after receiving this message and adds its data to the message. Message reception is done using a low power wake up the receiver. This WURx comes at the cost of a short communication range between nodes. The range limitation is overcome by hopping messages over other nodes to the receiving gateway.

A node in the network is woken up by transmission of one of its neighbours. After wake up, the node waits for its important incoming links before transmitting itself. The nodes learn about these important links during the exploration round of the algorithm. The important links together form a Direct Acyclic Graph of the network of nodes. This DAG is special in the sense that in this DAG all nodes can be reached by the source node and all nodes can reach the gateway. Therefore, if all nodes wait for their incoming links, all data can be gathered by the gateway with each node transmitting once. Network simulations for random input networks with 25 nodes show that a correct DAG solution is always found. However, in 6,% of these networks, 1 node is missing in the solution, and in 2 % of the networks, more than 1 node is missing in the solution.

Robustness of the network depends on the probability that a transmitted message arrives at the other nodes. With the WURx, it is shown that for a single link between nodes this probability is 99 %. With multiple nodes transmitting, a collision-avoidance mechanism is used. With this mechanism and multiple nodes that want to transmit, the arrival rate is tested with a probability of 97% in the case of no hidden node. In the case of hidden nodes, the arrival rate is tested with a probability of 94 %. A transmission from a hidden node is detected by toggling an operational amplifier at the input of the WURx. This shortly increases power consumption but the detection range of transmissions is increased as well.

Although it cannot be guaranteed that all data will be collected in each data gathering round, or even that data will arrive at all, it is proven with implemented hardware that data arrival of 95 % can be achieved with different small networks of 5 nodes.

An RF energy harvester is implemented that serves as an energy source for the nodes. This energy harvester is comparable to related work.

With these obtained results, the main research question is answered. With the implemented system, it is shown that data measurements are gathered with time correlation in a network of low power energy harvesting nodes. With the proposed algorithm, the nodes need to transmit once in the defined time interval. With a minimal harvested power of 6 μW, data can be gathered every 15 minutes.

Chapter 10

Future Work

With the work done in this thesis it is shown that the proposed algorithm can run on low power energy harvesting nodes. Future work can improve this implementation and the achieved results by several things that are highlighted in this chapter.

Hardware Improvements

- Increasing the efficiency of the RF energy harvesting circuit will increase the range that the nodes can be powered. Increasing the efficiency of the WURx can increase the communication range of the nodes.
- By achieving higher harvesting range and communication range, the system can be used by more use cases.
- The WURx should have an additional small bandwidth filter to limit the influence of the high power RF signal that powers the circuit.
- For practical considerations, the receiving and transmitting antenna can be combined to one antenna by using a RF switch. In theory the harvesting antenna can be combined with this antenna as well using a multiband antenna. This will minimize the physical space of the nodes.
- No special attention is made to the antenna design. Using an improved antenna, which receives more power, harvesting and transmitting ranges can be increased.

Topology

Potentially, reliability in the multihop relaying network can be increased by dividing the nodes in smaller networks where these smaller networks have a battery powered node which can communicate to the gateway directly. This has to be researched in depth.

Link Layer

Although the probability of collisions or failing links is a few percent, the probability grows significantly when multihop networks are used as done in this work. Small decrease in the collision probability can therefore significantly increase overall arrival rate. Error correcting codes could be added to correct bit mistakes thereby decreasing the messages that are discarded.

Network Layer

As shown in Section 7.2, situations can occur where a small part of the network cannot be solved. This is because a decision has to be made which could create undesired cycles in the network. Solving this problem would strengthen the algorithm that is shown by this work. Furthermore, the algorithm is static in the sense that it does not adopt to changes in links between nodes. If links do not longer exist due to changes in environment. the node will either not be informed or a timeout will occur each round. Timeouts prevent the network from stalling but introduces delay. A dynamic decision protocol should take care of the decision whether links are still valid or need to be updated.
A more in depth research and extended simulations about different network topologies can give more information over how the algorithm behaves on these network topologies.

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Appendix A

Appendix

A.1 Algorithm Simulation Results

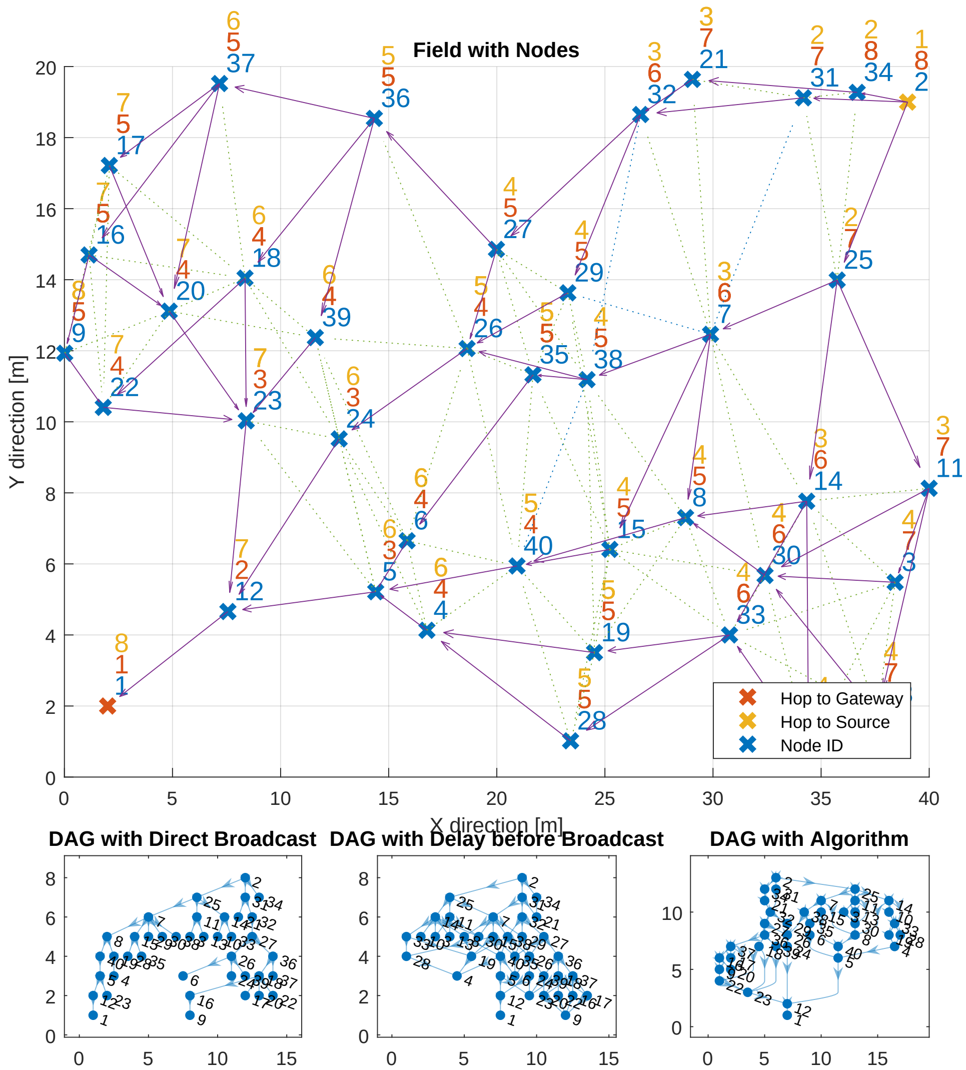

Figure A.1: **Matlab Simulation of a random placed network with N=40.**

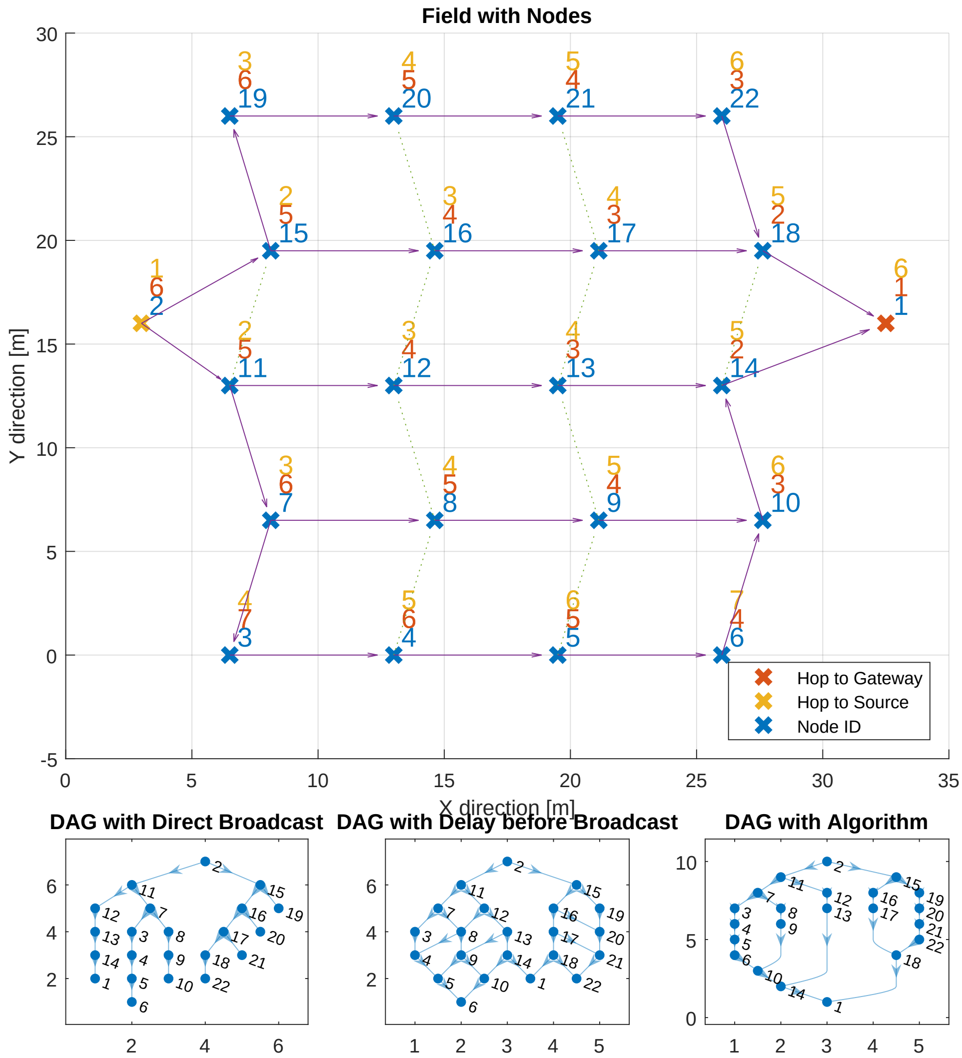

Figure A.2: **Matlab Simulation of a grid network.**

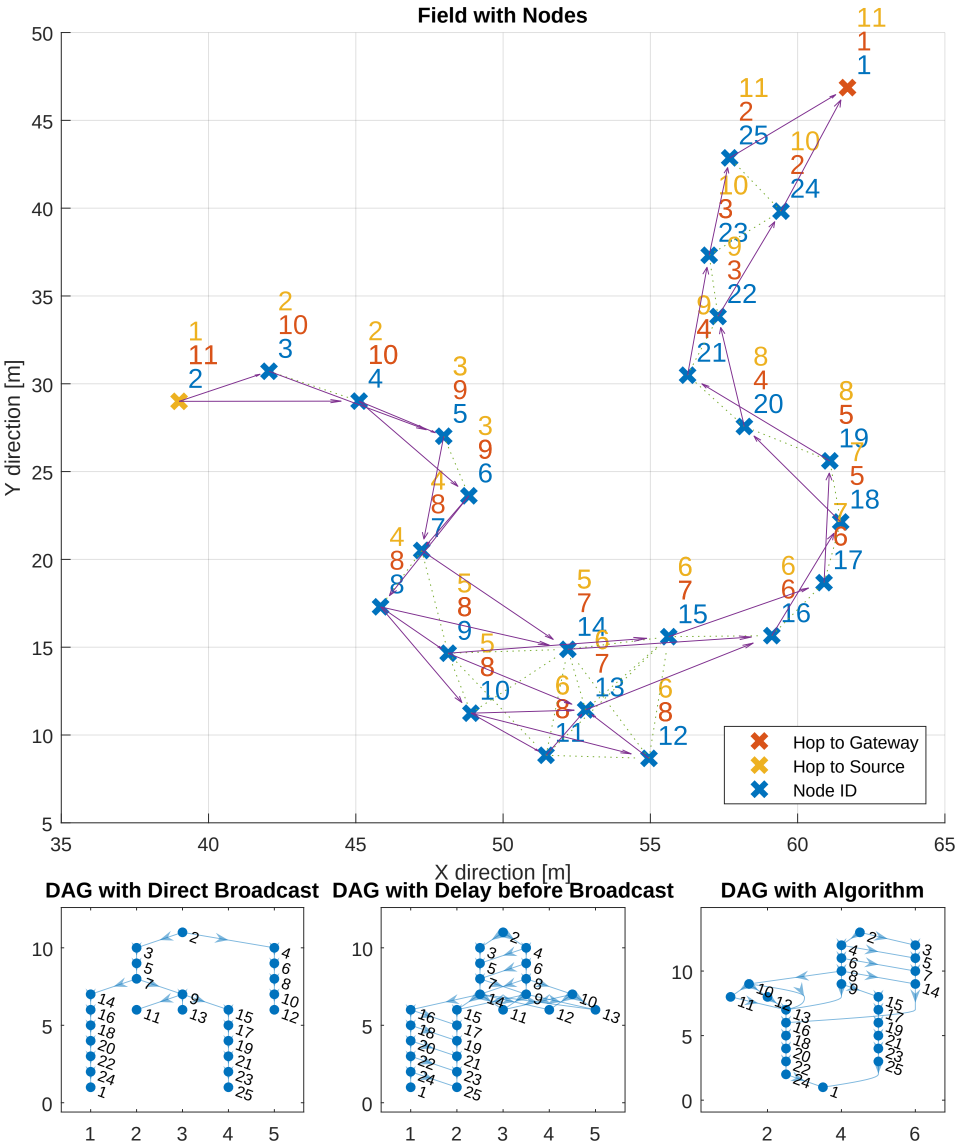

Figure A.3: **Matlab Simulation of a line network with random curve, Distance between nodes = 3. Interdistance = 8m.**

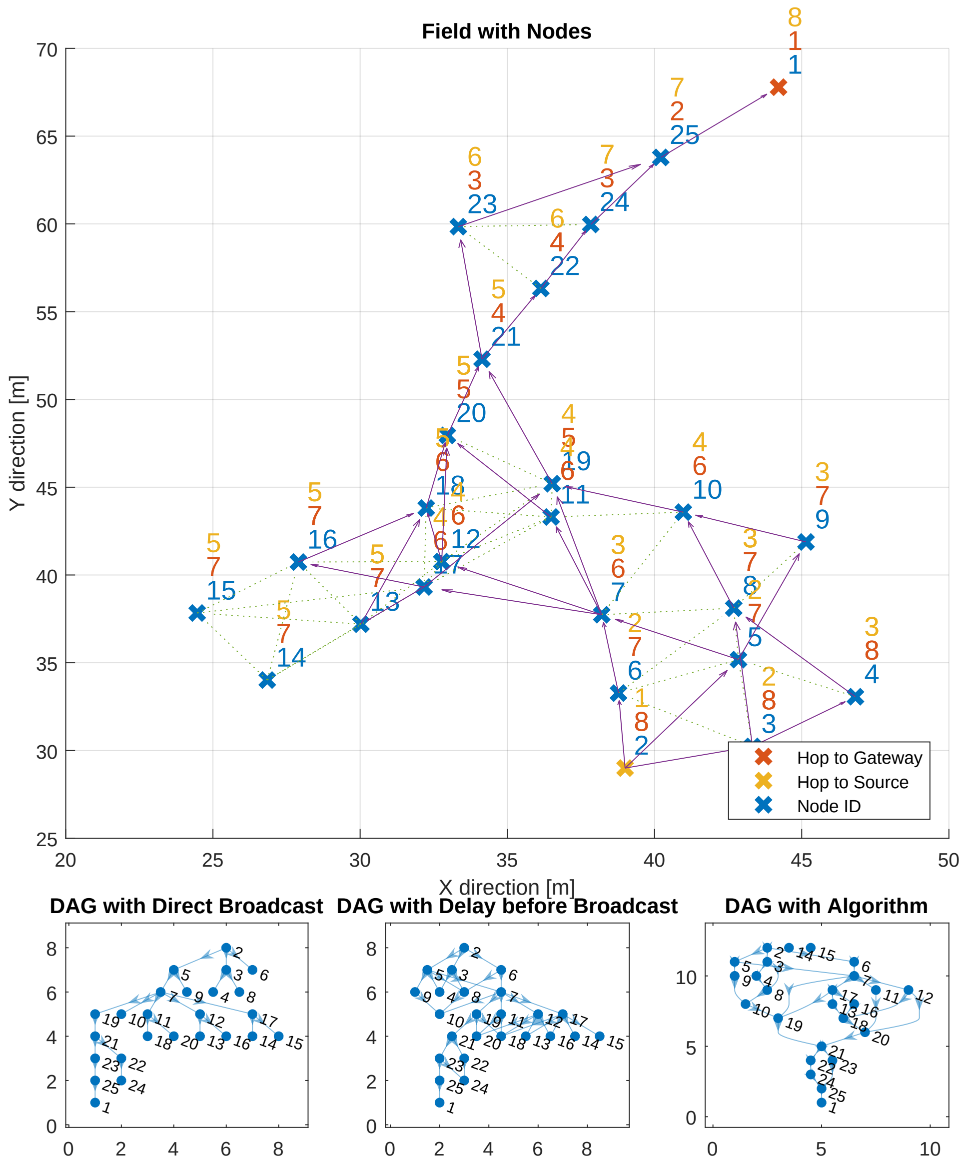

Figure A.4: **Matlab Simulation of a line network with a strong random curve, Distance between nodes = 5. Interdistance = 8m, two nodes are not solved with the algorithm.**