Energy Management System
for a
Wireless Indoor Climate Sensor

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Preface

The Bachelor Graduation Project of Electrical Engineering at Delft University of Technology requires its participants to work out a design, based on an proposal by a group in the faculty of Electrical Engineering, Mathematics and Computer Science. A proposal by Dr. Ir. Michiel Pertijs of the Electronic Instrumentation Laboratory was to design a wireless sensor node, using sensors developed by this department. This thesis describes the design and implementation of the energy system of this sensor node.

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Abstract

The Electronic Instrumentation Lab at Delft University of Technology desired to have a demonstrator for low-power temperature and humidity sensors they developed, in the form of a wireless sensor node. This thesis presents the design of the energy management system of this node. The primary design goal was to allow the sensor systems to run for as long as possible, at least a year, without any kind of service or human intervention, doing so in indoor lighting conditions.

Using the state of the art of such energy systems in sensor nodes, a concept consisting of energy storage combined with energy conditioning was generated. A single cell lithium-ion polymer battery and an ultra low quiescent current linear voltage regulator (the Texas Instruments TPS78233) were used to implement this concept. Switching voltage regulators with buck and buck-boost topologies were also considered, as well as combinations of linear and switching voltage regulators, but these ultimately turned out to be highly inefficient when the sensor is idle and the output current is in the order of microamperes. The lithium-ion polymer battery chemistry was chosen because it is widely available in high capacities, it has a relatively low self-discharge current and it can be charged.

As the ultimate goal of this design was to let the sensor systems run for as long as possible, and not just a year, energy harvesting techniques were also researched. It was found that amorphous solar cells were the best option for this design, as this was the best commercially available technology for harvesting energy at low light levels at the time. A promising new solar cell technology for this purpose is the dye-sensitized solar cell, however, these were only available as do-it-yourself kits at the time, and project time constraints withheld the usage of this technology because of that. Energy harvesting based on radio-frequency electromagnetic waves was also considered, but it was found that this technology did not provide enough power within the size and budget constraints.

As such, a secondary concept was generated, using a 100x50 mm amorphous solar panel by Sanyo Energy and a lithium-ion charger circuit based on the Maxim MAX17710. The charging circuit consists primarily of a largely integrated switching voltage regulator using the boost topology.

Both of these systems were implemented on a single circuit board along with the other sensor systems, designed such that it was possible to switch between the two energy systems easily. When this circuit board was completed, measurements were done to determine the average output current of the charger under office light conditions. When it is assumed that these conditions last for about ten hours per day, the average current output was found to be approximately 45 µA. Furthermore, the average supply current for the sensor was found to be 53.4 µA. Using these numbers, the minimum capacity for the battery to run the system for a year was determined to be 1300 mAh when no harvesting system is used, and 213 mAh when the solar panel is used.
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\( c \) \hspace{1cm} \text{Battery capacity in Ah.}
\( C \) \hspace{1cm} \text{Capacity in Farads.}
\( \delta \) \hspace{1cm} \text{Duty cycle.}
\( \eta \) \hspace{1cm} \text{Normalized efficiency (from 0 to 1).}
\( f_s \) \hspace{1cm} \text{Sample rate in Hz.}
\( I \) \hspace{1cm} \text{Current in Amperes.}
\( I_I \) \hspace{1cm} \text{Input current.}
\( I_O \) \hspace{1cm} \text{Output current.}
\( I_Q \) \hspace{1cm} \text{Quiescent current.}
\( I_{bat,max} \) \hspace{1cm} \text{Maximum expected battery current.}
\( P \) \hspace{1cm} \text{Power in Watts.}
\( P_I \) \hspace{1cm} \text{Input power.}
\( P_O \) \hspace{1cm} \text{Output power.}
\( P_{dis} \) \hspace{1cm} \text{Power dissipation in a regulator, or } P_I - P_O.
\( Q \) \hspace{1cm} \text{Charge in Coulombs.}
\( Q_{bat,min} \) \hspace{1cm} \text{Minimum battery capacity.}
\( Q_{meas} \) \hspace{1cm} \text{Charge in Coulombs used for a single measurement.}
\( R \) \hspace{1cm} \text{Resistance in Ohms.}
\( R_{load} \) \hspace{1cm} \text{Load resistance.}
\( R_s \) \hspace{1cm} \text{The resistance in series with the load and the battery in a linear voltage regulator.}
\( R_{sh} \) \hspace{1cm} \text{The resistance in parallel with the load and the battery in a linear shunt voltage regulator.}
\( T \) \hspace{1cm} \text{Temperature in Kelvin.}
\( T_C \) \hspace{1cm} \text{Cold temperature in a Carnot engine.}
\( T_H \) \hspace{1cm} \text{Hot temperature in a Carnot engine.}
\( T_{operate} \) \hspace{1cm} \text{The amount of time in seconds which the sensor must operate for without service.}
\( U \) \hspace{1cm} \text{Voltage in Volts.}
\( U_I \) \hspace{1cm} \text{Input voltage.}
\( U_O \) \hspace{1cm} \text{Output voltage.}
\( U_{DO} \) \hspace{1cm} \text{Dropout voltage, or } U_I - U_O.
\( U_{bat} \) \hspace{1cm} \text{Battery voltage.}
\( U_{bat,min} \) \hspace{1cm} \text{The minimum battery voltage tolerated by the sensor module.}
\( U_{bat,max} \) \hspace{1cm} \text{The maximum battery voltage tolerated by the sensor module.}
Chapter 1

Introduction

Typically, when large environments are to be monitored, several sensors have to be installed on-site to gain acceptable results. These sensor modules may then be connected to each other and to a central location where the data is used, by means of a sensor network. To minimize costs of such a network, today’s sensor nodes are usually designed to communicate with each other wirelessly and operate autonomously. Additionally, it is anticipated that the market demands a deploy-and-forget approach for the sensor nodes - the nodes should be able to operate without service for years [1]. Also, the sensors are to be kept small to not get in the way.

This specifically means that the power management of such a sensor node is extremely important. On the one hand, sensors have to be small, which means that any battery used needs to be small, but on the other hand, the sensor has to operate for a very long time without replacement of the battery. Therefore, the power consumption of the sensor systems has to be minimized.

To take the next step in making sensors even smaller and longer lasting, the Electronic Instrumentation Laboratory at Delft University of Technology has designed a low-power temperature and humidity sensor. For marketing and presentation purposes, they required to have a demonstrator for these sensors, in the form of a wireless sensor node, as this would be the primary application of the sensor. The sensor node had to measure the temperature and humidity in a room and send this data to a central location wirelessly. The energy system also had to be wireless.

A problem analysis with the client spawned a detailed program of requirements for the complete sensor node, which can be found in the appendix. A task division was subsequently made, dividing the design of the module into the control system, wireless system and the energy system. Refer to [4] and [5] for the design process of the control system and the wireless system, respectively. The goal of this thesis is to present the design of the energy management system for this sensor.

First, in chapter 2, the task division among theses as stated above is presented. Then, in chapter 3, information about the current state of the art of such energy systems is gathered from literature. In chapter 4, possible concepts for solving the design problem are listed, and subsequently a selection is made by comparing the concepts. In chapter 5, the selected concepts are implemented. Finally, chapter 6, a prototype of the designed system is tested, and evaluated in the subsequent chapters.
Chapter 2

Project overview and task division

As stated in the introduction, the development of the sensor node was subdivided into three major tasks: design of the control unit for the sensor [4], development of the wireless system [5] and the development of the energy system (presented in this thesis). Each task was carried out by a group of two students, and these groups would each write a thesis about their task.

This chapter describes the reasoning behind this task division. First, in section 2.1, a block diagram of the entire system is presented. Then, in 2.2, the subsystems from the diagram are divided among the three groups. It may prove useful to refer to the appendix for the system requirements while reading this chapter.

2.1 System block diagram

The purpose of the designed system is to control the MIST1431 sensor and transmit the measurement data wirelessly to a computer. Furthermore, the sensor module has to also be wireless in terms of power supply. From these specifications, the block diagram shown in figure 2.1 was made. The functions of the modules are described in the list below.

![Block diagram of the to be designed system](image)

**MIST1431 sensor** The MIST1431 sensor block consists of the actual sensor and any necessary additional components or support systems required for correct operation.

**Control** This block is in charge of configuring and controlling the MIST1431 sensor and the wireless transmitter or transceiver. If bidirectional wireless communication is used, the control block is also in charge of processing any commands given by the computer. Finally, the control block is in charge of placing the system in sleep mode when a sample has been processed, and waking it up again when a new sample was to be made.
Transmitter and receiver or transceivers  These blocks take care of respectively sending and receiving data wirelessly from the sensor module to the computer. As the data is to be given to the transmitter by the control block processed on the computer, no intelligence or understanding of the data packets is required in this block.

Power supply  This block supplies energy to the sensor module. As stated in the requirements, it must last at least a year without any form of service.

Computer  The computer is only required to display the sensor measurements to the user. If bidirectional communication is implemented, the computer may also be used to send commands to the sensor module.

2.2 Task division

As the system is to be designed in a group of six students and time is limited, a proper subdivision of design tasks was necessary. As an additional constraint to the project, three theses were to be written, and so the team was split into three groups of two students each.

The first group would be in charge of the design, implementation and documentation of the sensor and control blocks. Additionally, this group would be responsible for writing and documenting all software for the control block and the computer. It should be noted that due to time constraints, the tasks of doing the actual programming were divided among the entire team. The resulting thesis is [4].

The second group would be in charge of the design, implementation and documentation of the wireless communication system and protocol. The resulting thesis is [5].

The third and final group would be in charge of the design, implementation and documentation of the power supply for the sensor module. The results of this group are presented in this thesis.

The reasoning behind this specific subdivision was that the three tasks were expected to take approximately equal amounts of time to complete. Additionally, they could be completed in parallel as their design is largely independent of one another.
Chapter 3

State of the art for energy management in wireless sensor systems

In this chapter, a literature study will be presented to gain insight in the current state of the art of power management for wireless sensor nodes. The results of this study will then be used to generate possible concept solutions in the next chapter, adhering to the Program of Requirements as presented in the appendix.

In section 3.1, a classification for sensor systems based on their energy management system is presented, and the subsystems required for these energy management classes are introduced. This classification was made by the authors to determine which subsystems needed to be researched. In sections 3.2, 3.3 and 3.4, a detailed literature study on those subsystems, energy harvesting, energy storage and energy conditioning respectively, is presented.

3.1 Energy management system topologies

To gain insight in the structure of wireless energy management systems, it was found to be helpful to first make a classification for such systems. After that, the structure of each class could be dealt with separately. The classification used is presented in this section.

3.1.1 Classification

Wireless energy management systems can all be placed in one of the following categories.

- **Pure energy storage**: all energy is contracted from a battery or some other energy storage system (such as a fuel cell), which must be replaced, recharged or refueled periodically.

- **Pure energy harvesters**: all energy is contracted from the environment. If, at any point in time, the energy influx is too low to sustain the system, the system simply powers down.

- **Energy harvesters with energy storage**: some or all energy is contracted from the environment. When the energy influx from the harvesting system is too low to sustain the system, the energy storage is used to keep the system up and running. When the energy influx is too high, the energy storage may or may not be recharged with the excess energy. The energy storage may have to be replaced or recharged externally periodically if the average energy influx from the harvesting system is too low to sustain the system.

Some systems using energy harvesting rely on an artificial source of energy, which is somehow injected into the environment elsewhere. An example of such a system is an RFID tag, which gets its energy from a nearby high power RF transmitter. Similarly, one could also say that an indoor sensor relying on photovoltaic cells requires the light to be on to function properly.
The primary characteristics of the three classes are shown in table 3.1. It is assumed in this table that only the energy storage requires maintenance. For example, if a battery is used, it may need to be replaced periodically, even if it is trickle charged by an energy harvesting system due to the charge cycle limit of most such systems.

<table>
<thead>
<tr>
<th>Class</th>
<th>Complexity</th>
<th>Maintenance</th>
<th>Uptime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure energy storage</td>
<td>Simple</td>
<td>High</td>
<td>Continuous</td>
</tr>
<tr>
<td>Pure energy harvester</td>
<td>Simple</td>
<td>None</td>
<td>Not guaranteed</td>
</tr>
<tr>
<td>Energy harvester with storage</td>
<td>More complex</td>
<td>Low</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

### 3.1.2 Required subsystems

Three kinds of subsystems are required to build up an energy management system for a wireless system, namely energy storage devices, energy conditioners and energy harvesters. This is shown in figure 3.1 by means of a functional block diagram for each of the three classes defined in the previous section.

![Figure 3.1: Subsystems of the energy management system](image)

It should be noted that, in some cases, the energy conditioners are not required. This is the case when the supplied energy already meets the requirements for the system it powers.

### 3.2 Energy harvesting

Energy harvesting, also called energy scavenging or power harvesting, is the conversion of ambient energy for practical use. While this definition includes techniques such as windmills used for example to keep land dry, this section will only focus on energy harvesting systems used to collect energy for use in electrical systems. Additionally, large-scale energy harvesting methods as reviewed in [6] will not be discussed, nor will energy harvesting methods that collect their energy from human input, as all these techniques are irrelevant within the scope of this thesis.
Table 3.2 summarizes the possible energy harvesting techniques, and their typical power densities. Note that the power density of RF radiation is specified per volume, while the other power densities are specified per surface area, due to the nature of the harvesting techniques.

Table 3.2: Comparison of energy harvesting techniques by their power densities [1]

<table>
<thead>
<tr>
<th>Source</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar (outdoor) (100 mW/cm²)</td>
<td>5–25 mW/cm²</td>
</tr>
<tr>
<td>Light (indoor) (100 µW/cm²)</td>
<td>5–25 µW/cm²</td>
</tr>
<tr>
<td>RF radiation</td>
<td>0.1–1 µW/cm³</td>
</tr>
<tr>
<td>Thermo-electric (∆T=5°C)</td>
<td>40 µW/cm²</td>
</tr>
</tbody>
</table>

3.2.1 Light

Photovoltaic cells can convert ambient light energy into electricity. They consist of semiconductors, which can absorb light and deliver this energy to electrical energy carriers. When n- and p- doped semiconductors are combined in a pn-junction, incident light is absorbed by the electrons and holes, which then generates a current in a desired direction [7].

Depending on the type of cell, the efficiency of readily available photovoltaic cells ranges from 5% to 30% [8]. Outdoors, on a sunny day, the sunlight has a power density of about 100 mW/cm², indoors, the light in an office has a power density of about 100 µW/cm² [9]. Therefore, with the given efficiencies, a photovoltaic cell that is used outdoors can produce 5 to 30 mW/cm²*, a cell used indoors 5 to 30 µW/cm²*.

Some types of photovoltaic cells are discussed below. Note, however, that this list is not exhaustive.

Crystalline Silicon-based

Crystalline Silicon-based (c-Si) cells are the most common used photovoltaic cells. They have a relatively high efficiency, but production is rather expensive. Additionally, they do not work too well under low-light conditions.

Amorphous Silicon-based

Amorphous Silicon-based (a-Si) photovoltaic cells were historically used in devices that require little power, such as pocket calculators, though recently they are also used as solar panels. They consist of a thin-film of amorphous (noncrystalline) silicon. Their efficiency is low relative to c-Si cells, namely 5 to 7 percent, however their production is simpler. This makes them less expensive than c-Si cells. Commercially available a-Si cells for indoor use have a maximum power density of 7 µW/cm² at a light intensity of 200 Lux.

Dye-sensitized

Dye-sensitized solar cells (DSSCs) are cells that consist of titanium dioxide dyed in a electrolyte solution. Efficiency of these cells is about 11%, higher than most thin-film cells. Commercialization of these cells has been held back due to problems with the stability of the dye. Therefore, these type of cells are not readily available, although do-it-yourself sets are.

3.2.2 RF radiation

In an urban environment radio frequency (RF) radiation is present. This can be converted into electrical energy by antennas, and therefore could be a possible energy source for a wireless sensor node. [10]

*Table 3.2 is taken from an older source, where the efficiency is assumed to be up to 25%.
The amount of RF background radiation is limited by national authority, which means a constraint on the maximum amount of energy which can be harvested. For example, in the Netherlands, the Health Council of the Netherlands advises the Dutch government and Parliament on the health effects of electromagnetic radiation, an example of such an advice is [11], concerning the long-term health effects of electromagnetic fields. Also, constraints on the size of a device which might want to use this method limit the amount of energy that can be harvested. These facts result in a maximum power density of 1 $\mu$W/cm$^3$ when harvesting RF radiation, as shown in [8].

3.2.3 Thermal

A temperature difference in a conductor results in a heat flow. This separates electrical charges, which in turn create a voltage. Thermoelectric generators produce electrical energy from temperature differences by using a thermocouple [10].

The energy that can be harvested from temperature differences is fundamentally limited by Carnot’s theorem:

$$\eta = 1 - \frac{T_C}{T_H}$$  \hspace{1cm} (3.1)

In this equation, $\eta$ is the efficiency of the Carnot engine, $T_C$ the colder temperature and $T_H$ the hotter temperature. For example, the temperature difference between 37 degrees Celsius and room temperature can therefore only result in an efficiency of about 5.5% [9].

3.3 Energy storage systems

Two of the three classes mentioned in section 3.1.1 require some form of energy storage. The primary requirement of pure energy storage systems are a low self-discharge rate, as the sensors typically have to remain active for longer periods of time while using little power. For energy harvesters with energy storage the primary concern is that the storage must be electrically rechargeable. Self-discharge rate is less important for such systems as the storage is recharged regularly.

3.3.1 Batteries

The easiest and by far most commonly applied method for implementing energy storage is using a battery. Many types of batteries exist, usually distinguished by their chemistry. Some commonly used battery chemistries which may conform to the requirements above are listed below. Note however, that this list is not exhaustive by any means.

Alkaline

Alkaline batteries are typically non-rechargeable and not suited for high drain devices, but they have a long shelf life and are cheap. As such, they are the most common type household batteries [12]. Their long shelf life comes from a very low self-discharge of only about 3% per year [13, pp. 11]. Because of this low self-discharge, they are suited for low drain devices such as remote controls, and thus also in sensor systems.

While rechargeable alkaline batteries do exist, they have a very small recharge cycle life, which may be as low as ten cycles [12]. As such, they are not suitable for energy harvesting systems.

Nickel metal-hydride

Nickel metal-hydride (NiMh) batteries are the most commonly sold type of rechargeable AA or AAA batteries [12]. While suitable for high-drain devices such as cameras, they are not very useful in low drain devices such as sensors unless trickle charged by an energy scavenging system, as their self-discharge rate is about 20% - 50% of their capacity every six months [14, pp. 12].
Lithium-ion/lithium-ion polymer

Lithium-ion (Li-Ion) batteries are now commonly used in commercial devices such as laptops, cell phones and cameras. Several subclasses of Li-Ion batteries exist, the most well-known one being Lithium-ion polymer, or LiPo batteries. They can be recharged numerous times without much degradation and offer relatively low self-discharge relative to NiMh batteries (approximately 5% per month [15]). However, they are not available as standard AA or AAA batteries, as their nominal cell voltage of 3.7 V is much higher than that of NiMh and alkaline batteries (1.2 V and 1.5 V respectively).

Silver-oxide

Silver-oxide batteries are notable for their flat voltage to charge curve and their extremely low self-discharge characteristics. Most coin cell batteries use this chemistry. However, these batteries lose their charge quickly when discharged at high currents (their effective capacity is decreased), in fact, standard Ag-NaOH coin cell batteries will only supply about half of their capacity when discharged at currents as low as 1 mA. Silver oxide batteries are not typically sold at capacities of above 200 mAh. Their nominal cell voltage is 1.5 V [16].

Zinc-air

Zinc-air batteries are notable for their high energy density. They are commonly used in hearing aid devices, where size and thus energy density is of particular importance [17]. However, they seem to not be widely available in higher capacities.

3.3.2 Supercapacitors

Another device which may be useful for the energy storage of a wireless sensor node is a supercapacitor. If a certain conventional capacitor has a capacitance of 10 mF, a supercapacitor, using the same form factor, can have a capacitance of 1 F [18].

Though development goes back to 1957, significant cost reduction due to breakthroughs in material science did not occur until the 1990s, making supercapacitors a relatively new technology.

The primary advantage of a supercapacitor over a battery is that they perform exceptionally well in terms of burst currents and they have an extremely high cycle life. While the former is not relevant in low power systems such as a wireless sensor, the latter means that an energy harvesting assisted energy management system can recharge the storage extremely often without maintenance due to failing energy storage.

On the other hand, supercapacitors also have several disadvantages over batteries when used as energy storage. One of these disadvantages is due to the nature of a capacitor. Unlike a battery, where the cell voltage remains relatively constant, the voltage on a supercapacitor depends on the amount of charge in it.

\[ U = CQ \]  

(3.2)

In this equation, \( U \) is the voltage on the capacitor, \( C \) is the (constant) capacity of the supercapacitor and \( Q \) is the charge on the capacitor in Coulombs. This means that they require a constant current source to be charged, and are best discharged using a current based load. Since virtually all loads which may occur in a sensor system are voltage based, a complicated energy conditioning device may be required to power the systems efficiently.

A second disadvantage is that supercapacitors have a very high self-discharge rate. Measurements in [19] show a self-discharge rate of 15% to 20% in just 24 hours for three supercapacitors.

3.3.3 Other systems

Besides batteries and supercapacitors, there are more ways to implement energy storage. Fuel cells are an example of such an energy storage method. However, such systems are not commonly used in sensor systems due to their relative cost, dimensions or other design constraints.
3.4 Conditioning the energy for use by the systems

Although methods for storing and harvesting energy have now been reviewed, the energy delivered to
the system by these methods typically does not yet conform to the requirements set by the processor,
wireless device and sensors. Such systems are typically designed to operate at a fixed supply voltage,
which may not deviate too much if correct operation is to be guaranteed. As such, voltage regulators
are typically employed to provide such supply voltages.

Note that, since multiple subsystems need to be powered by the power management system,
several of such supply voltages may need to be generated. As such, multiple voltage regulators may
be needed. Additionally, there may well be systems which are only active when the sensor module
is sampling or transmitting sensor data, which may pull orders of magnitude more current than the
systems which are always on. This means it may be beneficial to use multiple voltage regulators, as
voltage regulators are usually designed to be efficient in relatively small output current ranges.

Wireless power management systems which utilize both an energy harvesting system and energy
storage will require an additional system, which correctly and efficiently charges the energy storage
using the harvested energy. These systems will be referred to as charge controllers. The primary
difference between a voltage regulator and a charge controller is that a charge controller typically
requires a more complex control system to adhere to the charging specifications of the energy storage
system used. Aside from this control system however, the operation of the voltage regulators used in
charge controllers are similar, if not identical, to regular voltage regulators.

There are three main classes of DC-DC voltage regulators distinguishable, namely linear, switching
and hybrid voltage regulators, where hybrid voltage regulators are a combination of the former two
classes [2]. Some linear and switching voltage regulation methods are discussed below, hybrid designs
are not discussed.

3.4.1 Linear voltage regulators

There are two methods to implement a linear voltage regulator. These two subclasses are series
regulation [2, Sec. 17.2] and shunt-regulation [2, Sec. 17.3].

Series regulation

Series regulation based linear voltage regulators work by placing a controlled resistive element, \( R_s \), in
series with the supply voltage \( U_I \) and load \( R_{load} \). This topology, using a transistor for \( R_s \), is shown
in [2, Sec. 17.2]. Output voltage \( U_O \) may then be computed as follows.

\[
U_O = U_I \frac{R_{load}}{R_{load} + R_s}
\]  

(3.3)

\( R_s \) is controlled in real time such that \( U_O \) remains constant. Negative feedback mechanisms are
employed to achieve this. A practical example of such a system may be found in [2, Sec. 17.2.1].

Efficiency

The efficiency of a series regulator is defined primarily by the loss in the resistive element
and, for lower output currents, the quiescent current \( (I_Q) \) of the voltage regulator. The latter is
simply the current flowing through the ground terminal of the voltage regulator, caused by the power
consumption of the internal systems. The efficiency of the regulator may then be derived as follows.

\[
P_O = U_O I_O
\]  

(3.4)

\[
P_I = U_I I_I = U_I (I_O + I_Q)
\]  

(3.5)

\[
\eta = \frac{P_O}{P_I} = \frac{U_O I_O}{U_I (I_O + I_Q)}
\]  

(3.6)

In these equations, \( P_O \) is the power delivered to the load and \( P_I \) is the power delivered to the system
and regulator by the source.
When $I_Q \ll I_O$, equation 3.6 reduces to

$$\eta = \frac{U_O}{U_I}$$  \hspace{1cm} (3.7)$$

**Input voltage range**  Since the output voltage of a voltage divider can never be higher than the input voltage$^1$, the input voltage of a linear voltage regulator must at least be equal to the output voltage. In practice, the lower bound for the input voltage is slightly higher still, defined by dropout voltage $U_{DO}$ as follows.

$$U_{I,\min} = U_O + U_{DO}$$  \hspace{1cm} (3.8)$$

In this equation, $U_{I,\min}$ represents the minimum input voltage for correct operation and $U_O$ represents the output voltage.

The input voltage of a linear voltage regulator is further bounded by the maximum voltages defined by the technology ($V_{I,max,tech}$) used and by maximum power dissipation of the resistive element $P_{dis,max}$. The latter is also dependent on output current $I_O$.

$$U_{I,max} = \min \left( \frac{P_{dis,max}}{I_O} + U_O, U_{I,max,tech} \right)$$  \hspace{1cm} (3.9)$$

**Output current range**  The output current range for a linear voltage regulator only has an upper bound, as defined by maximum current handling capability of the resistive element $I_{max,tech}$ (it has a maximum because it is not linear in practice) and the maximum power dissipation as follows.

$$I_{O,max} = \min \left( \frac{P_{dis,max}}{U_I - U_O}, I_{max,tech} \right)$$  \hspace{1cm} (3.10)$$

The output current for a linear voltage regulator only has a lower bound in theory, defined by the maximum resistance of the resistive element. As transistors are usually employed to implement the controlled resistive element, this maximum resistance is defined by the leakage current of the transistor. However, as these leakage currents are typically very low, the internal systems in the voltage regulator usually provides enough of a load to overcome this leakage current.

**Shunt regulation**

Shunt regulation works similarly to series regulation, but series resistance $R_s$ is now fixed to a certain value, and regulation is done by varying a shunt resistance (i.e. parallel to the load), $R_{sh}$. The output voltage may then be computed as follows.

$$U_O = U_I \frac{R_{load} + R_{sh}}{R_{load}}$$  \hspace{1cm} (3.11)$$

In this equation, $U_I$ represents the input voltage, $U_O$ represents the output voltage and $R_{load}$ represents the load resistance.

For correct operation, $R_s$ is bounded by the minimum voltage difference between input and output voltage and the maximum current as shown in equation 17.24 in [2]. As such, $R_s$ will typically be rather small.

Shunt regulators require input and output capacitors for the same reasons as series regulators - they suppress transients and may be required for stability of the feedback mechanism.

**Efficiency**  In stead of deriving the efficiency of the shunt regulator, it will prove more useful to derive the total input current. To do this, write down Ohm’s law for $R_s$ and then rearrange it to get the input current as a function of the other terms, as follows.

$$U_I - U_O = I_I \cdot R_s$$  \hspace{1cm} (3.12)$$

$^1$Barring negative resistances, which do not exist in practice.
The most important bit of information which should be gathered from this equation is that the input current is in fact not dependent on the output current, or, alternatively, the power supplied by the source is independent of the power supplied to the load. This means that shunt regulation is not suited for a wireless sensor node, as the output power peaks periodically for a short period of time and decreases to near zero for the rest of the time. Since the supplied power must be greater than the peak delivered power to conform to conservation of energy, the source would constantly have to deliver at least the peak output power. This is clearly unacceptable. As such, further evaluation of shunt regulators are beyond the scope of this thesis.

3.4.2 Switching voltage regulators

Switching voltage regulators use a different method to regulate the output voltage, which eliminates the resistive losses in a linear voltage regulator. While the topologies listed below are quite different, they all rely on the principle of using a switch for regulation, in stead of using a resistive element. This is much more efficient, as an ideal switch does not dissipate any power in open nor close position, while resistive elements do.

On the other hand, switching voltage regulators are often more costly and more complicated to design. Additionally, they produce electromagnetic interference due to their switching nature, which has to be taken into account.

The following sections briefly describe the most commonly used switching voltage regulator topologies.

Buck converters

A buck converter is typically used when the input voltage is significantly higher than the output voltage, as, in such a case, a linear voltage regulator is highly inefficient.

A basic buck converter is shown in figure 3.2. When the switch is closed, the inductor is charged by the source voltage, and as such, the current through the load increases. When the switch is opened, the inductor is discharged through the diode and the load, decreasing the current. By repetitively opening and closing the switch at some duty cycle $\delta$, the output current and thus voltage can be regulated. As in linear voltage regulators, negative feedback principles are used to determine the duty cycle for a specific input voltage and load resistance.

As with a linear voltage regulator, the input voltage of a buck converter must be higher than the output voltage, otherwise the inductor current can never rise. The maximum input voltage is defined by the technology used to implement the switch and the controller.

The output current is limited by the maximum current of the switch, diode and inductor. Additionally, the output current typically has a significant lower bound as well. Fixed resistors are sometimes placed parallel to the output capacitor and the load to ensure that the output current will always be high enough, but this of course comes at a loss of efficiency.

The losses of a switching voltage regulator under normal conditions can be primarily attributed to transient behavior of the opening and closing of the switch and the power dissipation in the diode. Sometimes, the diode is replaced by a second switch to improve efficiency at the cost of design complexity. At lower output currents, the quiescent current may also become significant. Typical efficiencies range from about 80% to 95%.
Boost converters

A boost converter is used when the output voltage must be higher than the input voltage.

![Basic topology of a boost regulator](image)

A basic boost converter is shown in figure 3.3. When the switch is closed, the inductor is charged by the source voltage. When the switch is opened, the inductor is discharged through the source voltage, the diode, and the load, decreasing the current and charging the output capacitor. While the switch is closed, the output capacitor provides the load voltage. Similar to a buck converter, the charge on the output capacitor and thus the output voltage can be regulated by adjusting the duty cycle of the switch.

As mentioned before, unlike linear voltage regulators and buck converters, the input voltage must be lower than the desired output voltage. On the other hand, the input voltage must be high enough to power the control logic. Additionally, if the input voltage decreases too far, the input current increases. For most sources this implies that their voltage decreases further, resulting in a vicious circle until the regulator shuts down completely. This would likely also destroy the source in the process. As such, a protection mechanism called an undervoltage lockout (sometimes abbreviated UVLO) is commonly employed, which shuts down the regulator gracefully when the input voltage is too low.

The output current is limited by the maximum current of the switch, inductor, diode and source. There is no theoretical lower bound for the output current.

Boost converters are typically slightly less efficient than buck converters, with typical efficiencies of no more than around 80%.

Buck-boost converters

A buck-boost converter may be used when the input and output voltage are comparable, and both up- and down-conversion may be required.

Two topologies exist, going by the same name [20]. The first consists of a buck converter followed by a boost converter. As these two converters have already been described above, no further attention is given to this topology. The other, sometimes called an inverting buck-boost converter, uses a different technique from the switching voltage regulators described before.

![Basic topology of a standard buck-boost regulator](image)

Figure 3.4 depicts a basic inverting buck-boost converter. It closely resembles a boost converter, with the exception that the diode is reversed. This results in the inductor only being discharged through the load and the diode (as opposed to also through the supply), which eliminates the requirement that the input voltage must be lower than the output voltage. However, it also implies that the output voltage is negative, hence the "inverting" in the name.

The input voltage of a buck-boost converter is only bounded by the minimum and maximum voltages required for the switch and the control logic to operate, as defined by the technology used.
However, as with boost converters, a low input voltage may result in destructive input currents. As such, buck-boost converters usually also incorporate an undervoltage lockout system.

The output current is limited by the maximum current of the switch, inductor and diode. There is no theoretical lower bound for the output current.

The sources of energy losses and typical efficiencies are comparable to those of boost converters.

Other converters

More topologies for switching voltage regulators exist, as do variations on the above topologies. For example, some systems employ transformers instead of inductors to allow for greater input to output voltage ratios, galvanically isolated regulators exist, etc. Such systems are beyond the scope of this study.
Chapter 4

Concept generation and selection

This chapter describes the basic design choices made for the energy management system. The concepts were generated based on the information as presented in chapter 3. The resulting concept is further implemented in chapter 5.

Section 4.1 presents a simple model for the current consumption of the sensor systems to approximate the average current consumption. Section 4.2 describes the selection of a system topology from the classes as described in section 3.1. Following those two sections is a section for each of the required subsystems for the selected topology, as depicted in figure 3.1: section 4.3 presents the energy harvesting system, section 4.4 presents the energy storage system, and finally, section 4.5 presents the energy conditioning system. Each of these sections starts with a list of concepts which could, in theory, fulfill the requirements depicted in the appendix and finishes with a subsection detailing the final concept selection.

4.1 Modeling the power requirements for the sensor systems

The current consumption of the sensor systems was modeled as being periodic and piecewise constant at two levels. These two levels are the sleep mode current consumption and the current consumption when the whole system is powered.

The sleep mode current consumption is assumed to be 2 µA for the microcontroller $I_{uC,\text{sleep}}$ [4], negligible for the sensor and 3 µA for the Xbee module $I_{xbee,\text{sleep}}$ [5]. In active mode, the current consumption is assumed to be 7 mA for the microcontroller $I_{uC,\text{active}}$ [4] and 40 mA for the Xbee module $I_{xbee,\text{active}}$ [5].

Note that it was later found out that the assumption that the Xbee was not the limiting factor in terms of how long the system has to stay active. As such, the Xbee module could be powered down long before the microcontroller could (the microcontroller had to stay active to control the MIST1431). Therefore, this model gave a rather pessimistic estimate.

Because of the large difference between the sleep mode and active current, duty cycle $\delta$ is very important. However, this value was unknown until the software was completed and the system could be tested. In the following estimates, it was assumed that the sensor would have to be active for 0.5 seconds to take a sample and transmit it in the worst case. From the requirements in the appendix it can be seen that the sensor has to take a sample every minute. Thus, the duty cycle would be 1/120.

Using this information, the average current consumption of the whole system may now be computed as follows.

$$I_{O,\text{av}} = \delta (I_{uC,\text{active}} + I_{xbee,\text{active}}) + (1 - \delta) (I_{uC,\text{sleep}} + I_{xbee,\text{sleep}})$$

$$\approx \delta \left( I_{uC,\text{active}} + I_{xbee,\text{active}} \right) + I_{uC,\text{sleep}} + I_{xbee,\text{sleep}}$$

$$= \frac{1}{120} \cdot 47\text{mA} + 2\mu\text{A} + 3\mu\text{A}$$

$$\approx 0.40\text{mA}$$

(4.1)

Thus, the average current of the sensor systems was expected to be approximately 0.40 mA.
4.2 Energy management class selection

As stated in section 3.1, three different kinds of energy systems for wireless energy management systems are distinguishable. Their primary characteristics are shown qualitatively in table 3.1.

As can be deduced from 3, the sensor is required to stay fully functional continuously for a year without replacing a battery, if a battery is used. This automatically means that a pure energy harvester cannot be used, unless it is guaranteed that the harvesting source is always available. From the energy harvesting sources listed in section 3.2, only background RF radiation is present at all times, and this harvesting based on RF radiation must be used if a pure energy harvester is to be used.

Unfortunately, it became clear from initial estimates that background RF radiation does not supply enough power to power the sensor node unless a very large antenna is used. Injecting additional radiation into the environment using a transmitter was also considered, but was quickly found to be very limited in terms of maximum distance between power supply and sensor node, as well as being highly inefficient. As such, a pure energy harvesting solution was not considered further.

The choice was now between using energy harvesting with energy storage or just energy storage. Before this choice could be made however, the energy harvesting solution had to be chosen. As such, the selection between using energy harvesting or not is deferred to the next section, by adding the option of not using energy harvesting at all to the list of concepts.

4.3 Energy harvesting system

As stated above, a choice must be made about whether or not to use energy harvesting techniques to recharge the battery. This depends on a cost versus gain optimization: of course, any harvesting technique will prolong the battery life, but the question is whether this prolonging effect is significant, and whether it is worth the cost in terms of money and design complexity.

4.3.1 Concept generation

A list of three common energy harvesting techniques is listed in 3.2. However, not all three of these energy harvesting techniques are useful in this design. First and foremost, thermal energy harvesting is not applicable in the design, as there is no reason to believe that a well-defined temperature gradient will occur in or near the sensor, because, if at all, this depends greatly on the placement of the sensor. Additionally, the user will likely not want there to be any temperature gradients near the sensor module, as it is in part a temperature sensor and such a gradient would influence the temperature readings.

Secondly, while a very good source of energy, as it always available, the energy which can be harvested per volume from background RF radiation is extremely low (table 3.2). Even though the initial power consumption estimates which were made at the time were lower than the 0.4 mA calculated in 4.1 (it was expected that at most 0.1 mA would be required on average) background RF radiation does not come close to powering the sensor node. Additionally, antennas are usually rather expensive, especially the larger antennas which would be required to harvest at least a remotely useful amount of energy.

Thus, only light remains. As can be seen in section 3.2.1, several techniques exist for harvesting energy from light.

**Crystalline silicon solar cells** These cells are the most used type of solar cell, and have therefore a high availability. They also have a high reported efficiency. However, this efficiency was measured under light from the sun; under fluorescent light, it can drop to only 1–2%.

**Amorphous silicon solar cells** These cells are less available than c-Si cell, as their reported efficiency is lower than that of c-Si cells. However, they are easier to manufacture and thus cheaper than crystalline solar cells. Additionally, under fluorescent light their efficiency is higher for the same
irradiance when compared to solar-like light, and as such, these cells are commonly used for indoor applications.

**Dye-sensitized solar cells** While this type of photovoltaic cell would probably be the best for the job, as they are relatively cheap but function very well indoors, these cells are not yet readily available. If used, it would have to be made from a do-it-yourself kit. As assembling such a kit would be costly in terms of time and relatively prone to failure due to inexperience with such systems, it became clear relatively quickly that this option would be infeasible.

**No harvesting** Finally, as stated in the introduction of section 4.3, not using any harvesting technique at all is a valid and reasonable option if the other techniques turn out to not be efficient enough to be worth the costs.

### 4.3.2 Concept selection

Table 4.1 shows a comparison of the three harvesting techniques. As the table shows, amorphous solar cells should be used if energy harvesting is used at all.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Indoor efficiency</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Amorphous</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Dye-Sensitized</td>
<td>++</td>
<td>- -</td>
</tr>
</tbody>
</table>

After some more research into available solar cells was done, it became clear that only approximately 100 µA at around 3 V is realistic indoors, for an amorphous solar panel of approximately 50x100 mm. This value is about a quarter of the estimated average current consumption, which would decrease the required battery size by approximately a factor 1.3. However, as the estimates are very dependent on the duty cycle of the transmitter current consumption, which was unknown at the time, no real conclusion could be drawn from this.

To deal with this, it was decided that the selection of whether or not to use energy harvesting would be postponed to after a full prototype was produced, so the average current could be measured. The current measurement would be done using a laboratory power supply in stead of a battery, so no battery would have to be selected and bought yet before the measurements. The required battery capacities were finally computed in chapter 6.

However, time was limited: only one circuit board design could realistically be ordered and soldered. As such, it was decided to implement both concepts on a single circuit board, one with energy harvesting and one without, such that no new circuit board would have to be designed and manufactured after the measurements, and subsequently the decisions were made.

### 4.4 Energy storage system

Regardless of whether a solar panel is used for recharging, a form of energy storage is required. The selection of the energy storage is made in this section.

#### 4.4.1 Concept generation

From section 3.3 it is clear that the first choice to be made is between using a battery or a supercapacitor – both of these are commonly used in sensor nodes. Other energy storage methods, such as fuel cells, were not considered due to time, budget and complexity constraints.

The primary requirements for the energy storage system is that it must last a year. In section 4.1 a rough approximation of the average current consumption of the sensor systems was made. Since the
sensor must last a year, the battery capacity may be computed by multiplying this average current with 24 hours per day and 365 days per year, which then equals approximately 3500 mAh.

Note that this calculation assumes that the 3.3 V rail current is equal to the battery current. This is not entirely accurate, especially when a switching voltage regulator is used, but then again, this is only a first order estimate.

Supercapacitor

Due to the high self-discharge rate of a supercapacitor, a supercapacitor can only be used in conjunction with an energy harvesting system which, on average, delivers more power than the average power consumption of the sensor node. This may seem trivial, however, this is not the case for batteries, as most initially charged batteries will be able to power the sensor module for a significant amount of time, even if the energy influx from the harvesting system is not high enough to completely support the system. This is because the self-discharge rate of batteries is much lower and their capacity is usually much higher.

An additional disadvantage of using supercapacitors is that they require a low input voltage step-up converter to power the sensor. This is because their voltage to charge curve is far from constant. If such a converter is not used, a significant part of the energy stored in the capacitor is lost, simply because the voltage drops below the operating voltage of the sensor quickly. Requiring such a converter increases design complexity and cost.

Even though supercapacitors seem to have many disadvantages, they are in theory still suitable for a sensor node such as ours, as long as the energy harvesting system provides enough power.

Batteries require a more detailed study, as so many different chemistries exist, and each chemistry has its own advantages and disadvantages. These are listed briefly below. Refer to section 3.3.1 for more information.

Alkaline

Using alkaline batteries is a viable concept for a pure energy storage based power management system, as self-discharge rates are very low. They can not be used in energy harvesting assisted systems, since they can not typically be charged, and alkaline batteries which can be charged have a very low cycle life.

Nickel metal-hydride

NiMH batteries can only be used in energy harvesting assisted systems, as their self-discharge rate is too high to sustain a year without replacement. However, they are easy to source, as this is the chemistry of choice for household rechargeable batteries.

Lithium-ion (polymer)

LiPo and Li-Ion batteries may be used in both energy harvesting assisted and pure energy storage systems, as they have a high cycle life, a low self-discharge rate, and are available in high capacities.

Note that silver-oxide batteries were mentioned in the literature review, but not considered. This was done because, while silver batteries are very suitable for most sensor systems due to their extremely low self-discharge rate, they do not meet the requirements of the to be designed system, for two reasons. First, they can not sustain the burst loads of the transmitter, at least not without a form of buffering energy, which would make for an overly complex system when compared to the other solutions. Secondly, they are hard to source for high capacities. The silver-oxide chemistry is typically only used in coin cells, which are usually too small for the required capacities with the energy density of the chemistry.

Zinc-air batteries were also not considered, primarily because they are hard to come by in the required capacity range. While some sources seem to mention that such high capacity zinc-air batteries do in fact exist [21], a supplier selling zinc-air batteries at larger capacities than those used in hearing aid devices could not be found.

4.4.2 Concept selection

In the previous section, four viable concepts were generated which may solve the design problem of finding an energy storage system for the sensor node. These concepts are compared qualitatively in
Table 4.2. The points on which the solutions are compared are complexity and, with a smaller weight, availability. By design complexity primarily the complexity of the energy conditioning circuits for the sensor systems and, if applicable, the charger are meant. In the availability column, the ease of acquiring the components is compared.

Table 4.2: Qualitative comparison of energy storage methods

<table>
<thead>
<tr>
<th>Concept</th>
<th>Pure energy storage</th>
<th>Energy harvesting assisted</th>
<th>Complexity</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercapacitor</td>
<td>No</td>
<td>Yes</td>
<td>-</td>
<td>o</td>
</tr>
<tr>
<td>Alkaline battery</td>
<td>Yes</td>
<td>No</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>NiMH battery</td>
<td>No</td>
<td>Yes</td>
<td>o</td>
<td>+</td>
</tr>
<tr>
<td>Li-Ion/LiPo battery</td>
<td>Yes</td>
<td>Yes</td>
<td>++</td>
<td>o</td>
</tr>
</tbody>
</table>

As can be seen from this table, an alkaline battery is the best power supply for a pure energy storage system based on the above points. For an energy harvesting assisted system, LiPo/Li-Ion batteries are the better choice.

However, since it was still not certain at the time whether or not an energy harvesting system would provide a significant amount of power relative to the consumption of the sensor systems, it was decided to use a Li-Ion/LiPo solution in both cases to make designing a system capable of both technologies simpler.

4.5 Energy conditioning for sensor systems

The final concept selection which had to be made was that of the energy conditioning system for the sensor systems. This selection is detailed in this section.

4.5.1 Concept generation

To ensure correct operation, the sensor systems required a stable power supply, with a well-defined voltage. From the other theses [4, 5] and the MIST1431 datasheet [22], it was found that the system requires 3.3 ± 0.3 V to operate, at a maximum burst current of approximately 50mA. This maximum current is largely due to the current consumption of the Xbee module in transmit or receive mode [5].

It is clear from the LiPo discharge curve as shown in figure 4.1 that LiPo cells do not meet the requirements above. As such, applying the battery voltage directly to the sensor systems was not an option.

Figure 4.1: Nominal discharge curve of a Li-Ion based cell discharged continuously in five hours [3]
Two major concept classes were considered for the voltage regulation system, based on system layout. The block diagrams of these layouts are shown in figure 4.2.

The primary reason for considering to use two voltage regulators as depicted in figure 4.2(b) is the assumption that voltage regulators designed for higher loads will typically use more power themselves. By using a secondary voltage regulator for the Xbee unit, the primary voltage regulator would only ever have to cope with much smaller loads, and thus a regulator more suited for low currents could be chosen. The secondary, less efficient voltage regulator could simply be turned off when the Xbee is not being used.

On the other hand, a good reason for only using one voltage regulator as shown in figure 4.2(a) was that it is less complex, smaller, and cheaper.

The following paragraphs list the completed concepts (i.e. with voltage regulation topology included) which were considered. For more information about the voltage regulator topologies mentioned, please refer to section 3.4.

**Single linear voltage regulator** By far the simplest and most obvious solution to the design problem is to use a single linear voltage regulator. It was initially assumed, however, that this would also be the least efficient solution by a long shot, which is why the other concepts were devised.

**Two linear voltage regulators** This solution, using layout 2, deals with the issue that voltage regulators capable of supplying the relatively high loads occurring while transmitting are typically less efficient at lower currents, as explained in the paragraphs explaining figure 4.2(b). However, it is more complicated than using a single linear voltage regulator.

**Single buck voltage regulator** While even more complex than the previous two solutions, switching voltage regulators may be more efficient in theory, as the excess input voltage is not necessarily dissipated. It is, however, vitally important that the buck regulator implementation is capable of regulating small loads efficiently, which is usually not the case. This is what makes this solution so complex.

**Single buck-boost voltage regulator** This solution is an improved version of the previous, as it is capable of handling battery voltages of around 3.3 V and less, as buck-boost regulators can also step-up their input voltage. This may occur when the battery is almost depleted, as can be seen in figure 4.1. However, as with the buck solution in the previous paragraph, the regulator must be designed carefully to minimize power consumption at light loads, or the additional ∼10% usable battery capacity may be lost due to regulator inefficiencies.
Linear voltage regulator and a buck voltage regulator  In this concept, a linear voltage regulator is used for the low power regulator block in figure 4.2(b), while a switching voltage regulator is used for the high power regulator. This solution thus deals with the design problems of the other two voltage regulation concepts involving switching voltage regulators, as the switching voltage regulator always has to regulate currents of about 40 mA when it is on. It is, however, the most costly solution.

4.5.2 Efficiency approximations

Before actually selecting which concept to use, some efficiency approximations had to be made. These are presented in this subsection. First, a small study of the state of the art of voltage regulators on the market now is presented. Subsequently, an approximation of the LiPo discharge curve is made, followed by the resulting efficiency estimates for the five concepts generated in the previous section.

State of the art for commercially available systems

Beginning with linear voltage regulators, a search was made for low quiescent current linear voltage regulators on the market today. To our initial surprise, a very good voltage regulator in terms of quiescent current was quickly found at Texas Instruments. The regulator in question is the TPS782xx series. This regulator will be discussed in more detail in section 5.2.2, the thing which is of importance here is that the quiescent current of this regulator is as low as 420 nA with no load, and the dropout voltage is only 130 mV at its rated load of 150 mA typically [23]. When placed in shutdown mode, the current drops even further, down to 18 nA typically. These values were considered to be the current state of the art and were used in the calculations in the last part of section 4.5.2.

No such practical information could be found for the buck switching voltage regulators, however. In fact, no regulators could be found which accept input voltages of under 4.5V for regulating down to 3.3V. As such, the regulator would probably have to have been designed using discrete components, which would make it highly unlikely that nominal efficiencies of even about 80% will be reached. Worse still, quiescent current in such regulators is usually extremely high when compared to the linear regulator above, in fact, one of the smallest switching voltage regulator in terms of output current offered by Texas Instruments (the LMR14203) consumes an unacceptable 1.35 mA [24] - over three orders of magnitude larger than that of the TPS782xx.

No information was found for buck-boost regulators. In the calculations in the last part of section 4.5.2, the same estimates as those used for standard buck regulators are used, as the topologies are rather similar in nature.

LiPo discharge curve approximation

As can be seen in figure 4.1, the discharge curve for a LiPo battery shows highly nonlinear behavior. To simplify the calculations in the following section, a piecewise linear approximation was made.

\[
U_{bat}(x) = \begin{cases} 
4.2 - 3x & \text{when } x < 0.1 \\
3.925 - 0.25x & \text{when } 0.1 \leq x < 0.9 \\
10 - 7x & \text{when } x \geq 0.9 
\end{cases}
\]  

(4.2)

In this function, \(x\) is the normalized amount of capacity discharged, or \(E_{\text{discharged}}/E_{\text{capacity}}\). This function was produced empirically from the curve in figure 4.1. It is shown as an overlay to this curve in figure 4.3.

Expected efficiency per concept

Using the information in the two subsections above, efficiency estimates may now be made for each solution.

Single linear voltage regulator  For a linear voltage regulator, the system efficiency may be calculated using equation 3.6, where \(I_O\) equals \(I_{O,av}\) from equation 4.1 and \(U_I\) equals \(U_{bat}(x)\). However, since \(I_Q << I_{O,av}\) in fact holds, equation 3.7 may even be used.
However, these equations assume that $U_I > U_O + U_{\text{dropout}}$ for all $x$, which is not the case. From figure 4.1 it can be seen that at a little over 90% discharge, the battery voltage drops below this threshold. It was assumed that the system would fail in this case, or $\eta = 0$.

The average value for $\eta$ may now be computed by integrating over $x$. Since $x$ is already normalized, the following equation holds.

$$\eta_{av} = \int_0^1 \eta(x) \, dx = \int_0^{0.9} \frac{U_O}{U_{\text{bat}}(x)} \, dx = U_O \left( \int_0^{0.1} \frac{1}{4.2 - 3x} \, dx + \int_{0.1}^{0.9} \frac{1}{3.925 - 0.25x} \, dx \right) \approx 0.776 \tag{4.3}$$

Thus, an average efficiency of 77.6% may be expected.

**Two linear voltage regulators** The derivation for the efficiency of this solution is in fact identical to that of just having a single voltage regulator, as all effects of quiescent currents were found to be so low that they were negligible in the derivation in the previous paragraphs. Thus, it may be assumed that this solution also provides an average efficiency of approximately 77.6%.

**Single buck voltage regulator** In this approximation, the efficiency of the switching voltage regulator is assumed to be around 80%, with an additional loss due to the significant quiescent currents of such a regulator (found to be around 1.35 mA in the first part of section 4.5.2). Also, as with the linear voltage regulators, the system is expected to shut down when around 10% of the battery capacity is remaining. Thus:

$$\eta_{av} = 0.8 \cdot \frac{I_{O,av}}{I_{O,av} + I_q} \cdot 0.9 \approx 0.165 \tag{4.4}$$

This means that a total system efficiency of only around 16.5% is expected!

**Single buck-boost voltage regulator** The derivation for this topology is identical to that of the buck converter, with the exception that the system will stay operational until the battery is completely depleted. As such, the final 0.9 term in the efficiency calculation may now be dropped. Thus:

$$\eta_{av} = 0.8 \cdot \frac{I_{O,av}}{I_{O,av} + I_q} \approx 0.183 \tag{4.5}$$

As expected, the efficiency is higher than that of the buck converter, but with 18.3% it is still way too inefficient to consider.
**Linear voltage regulator and a buck voltage regulator**  The derivation for this layout requires two separate efficiency derivations, one for the linear voltage regulator and one for the switching voltage regulator. The derivation for the linear voltage regulator is done first.

Since the linear voltage regulator(s) now no longer supply the whole system, the average current used in the computation for this part needs to be revised to ensure that the quiescent current is still insignificant to it. This average current is computed as follows.

\[
I_{O,av} = \delta I_{uC,active} + (1 - \delta) I_{uC,sleep} \\
\approx \delta I_{uC,active} + I_{uC,sleep} \\
\approx 0.061 \text{mA}
\]  
(4.6)

As the average current is still much larger than the quiescent current of the regulator (within 1%), the system efficiency calculated for the linear-only concepts earlier still holds. This efficiency was 77.6%.

Next is the computation for the switching portion of the system. This may be computed in the same way as in equation 4.4. However, the average current when the regulator is on is now 40 mA, as the regulator will only be on when the Xbee is actually powered. Note that sleep mode currents for the switching regulator are ignored here.

\[
\eta_{av,switching} = 0.8 \cdot \frac{I_{O,av}}{I_{O,av} + I_q} \cdot 0.9 \approx 0.696
\]  
(4.7)

Thus, the efficiency for the switching portion is still lower than what would have been the case when the linear voltage regulator was used. Since this is the only conclusion which is really necessary to compare the concepts and the exact derivation is relatively complicated, this is beyond the scope of this thesis.

### 4.5.3 Concept selection

Now that the efficiencies have been calculated in the previous section, the concepts can be compared. The comparison is made in table 4.3. Aside from efficiency, the concepts were compared in terms of design complexity and cost as well.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Efficiency</th>
<th>Complexity</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single linear regulator</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Two linear regulators</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Buck convertor</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buck-boost convertor</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Linear and buck convertor</td>
<td>o</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As can be seen in the table, it is clear that a single linear voltage regulator such as the TPS782xx is by far the best option.
Chapter 5

Implementation of the voltage regulator and optional harvesting system

Chapter 4 described the process of generating and selecting a concept for the to be designed energy system. As quickly became clear in said chapter, it was too hard to determine whether or not an energy harvesting system would provide a significant amount of energy relative to the energy consumption of the sensor systems, due to high uncertainties in the model for the energy consumption of these systems.

Because of these difficulties and uncertainties, two possible concepts were selected to be implemented. In the first of these concepts, an amorphous silicon solar panel would be used to charge a lithium-ion polymer battery. This battery would then power the sensor systems. In the second concept, the energy harvesting system would simply not be used, and the system would run on the battery until it depletes, at which point it must be replaced. As stated in the requirements in the appendix, replacement of the battery may not occur more frequently than once per year.

This chapter describes the steps which were taken to implement these concepts. In section 5.1, the implementation of the energy harvesting system for the first concept is described. Section 5.2 then does the same for the voltage regulator in the second concept.

5.1 Implementation of the energy harvesting system

The first system which was designed was the energy harvesting system. This system includes the solar panel and the charge controller circuit. The battery selection was not done until the system was finished up to the point where it could be tested.

5.1.1 Functional block diagram

The first step to take in any design process is to produce a block diagram, to define the specific tasks of the subsystems in the to be designed system. The block diagram for the energy harvesting system is shown in figure 5.1.

From the subsystems in this block diagram, the solar cell, charge controller and linear voltage regulator had to be selected and implemented. Additionally, the interfacing between the control unit and the energy system required additional circuitry, as the control unit can only handle voltages of up to 3.3 V. The next section describes how the primary components for these systems were chosen.

Note that the battery is not selected in this section yet - as stated before, this will be done after the results have been presented. Also, the "sensor systems" block is explained only in the block diagram as a placeholder for the rest of the sensor module, of which the design is described in [4] and [5].
5.1.2 Component selection

This section describes how the primary components for the subsystems as shown in the block diagram in figure 5.1 were chosen, component by component.

Amorphous solar cell

While a number of producers are available for this type of cell (e.g., next to Sanyo, Solens in France and VHF Technologies in Switzerland), there are barely any distributors of these cells. Also, the only amorphous solar cells sold by these distributors are made by Sanyo Amorton.

This company uses amorphous solar cell technology to create solar cells that can be used indoors and outdoors, and to create photosensors which can be used in mobile phones. The indoor solar cells only differ from each other in their dimensions.

The selected solar cell is the AM1816-CA by Sanyo Energy. This cell was simply chosen because it has the largest available dimensions. Operating at 200 lux, it has an output voltage of 3 V and an output current of 84 \( \mu \)A. At 50 lux it has an output of 2.6 V and 21 \( \mu \)A. Extrapolating from these values using [25, pp. 7], at 500 lux it should operate with an output voltage of about 3.3 V and an output current of 210 \( \mu \)A.

Charge controller

For the selection of the charge controller, several energy harvesting integrated circuits were researched, and a selection was made from these options. These options researched were the MAX17710 by Maxim [26], the BQ25504 by Texas Instruments [27] and the LTC3105 by Linear Technology [28].

**MAX17710** [26] The MAX17710 is an energy harvesting, LiPo battery protection and linear voltage regulator integrated circuit, requiring little external parts. It utilizes a boost converter based regulator to step-up the input voltage coming from the solar panel to the battery voltage for charging.

Unlike the other two charge controllers however, this circuit does not support maximum power point tracking (MPPT) functionality, stating that "**MPPT systems must measure the current and voltage, multiply to determine power, and make decisions to improve the power. These required measurements automatically significantly increase the quiescent current budget by tens of \( \mu \)A**" [26, pp. 12].

It is notable when compared to the other circuits for having an integrated linear voltage regulator which conforms to our requirements, making this integrated circuit effectively the only major component required for the whole energy management system. It is even possible in this circuit to turn off the high current mode voltage regulator and only leave a very low current and more efficient voltage regulator running, but unfortunately this current is too low to sustain the microcontroller when it wakes up. Thus, this feature can unfortunately not be used.

The quiescent current of this regulator is only 725 nA for the battery when the voltage regulator is used. When the internal voltage regulator is not used, it even drops to 1 nA. However, it requires at least 1 \( \mu \)W of power from the solar panel for the charging system to operate.

The MAX17710 comes in a tiny 3x3x0.5 mm UTDFN surface-mounted package with an exposed pad. The exposed pad specifically means that it will be hard to solder - an oven or hot air soldering tools were expected to be required.
**BQ25504 [27]** The BQ25504 is an ultra low, high efficiency boost converter based charger with MPPT functionality. It is not designed specifically for LiPo batteries, but is instead configurable with external resistors and voltage dividers to meet the requirements of the energy storage device it has to charge.

It is notable for having a very low minimum input voltage for the energy harvesting input of only 80 mV. Additionally, it boasts the lowest quiescent current of all the integrated circuits which were researched, being only 330 nA. However, it is disputable whether quiescent currents this low can be reached in the whole system, due to the requirement of an additional linear voltage regulator. Also, it is not clear from the datasheet whether the external voltage dividers were accounted for in this quiescent current measurement.

The BQ25504 comes in a plastic quad flatpack no-lead (PVQFN) package 3x3x1 mm in size.

**LTC3105 [28]** The LTC3105 is a 400 mA step-up DC-DC converter with maximum power point control. It has integrated charge circuitry for Li-Ion based batteries (a LiPo battery is a specific type of Li-Ion battery) and a low power linear voltage regulator built in. Unfortunately, however, this voltage regulator can only supply up to 6 mA, which is not enough to run even only the microcontroller, which requires 7 mA when active [4].

It is specifically notable for combining relatively low part count for a charge controller with an MPPT and for being easy to source – Farnell, the electronics supplier of choice for the faculty, carries this integrated circuit. Additionally, it comes in an MSOP package - this is a surface-mount leaded package without exposed pad, making soldering comparably easy.

The catch turned out to be the quiescent current, however, coming in at 24 µA. Note that this is almost two orders of magnitude greater than that of the other charge controllers.

Table 5.1 shows a quantitative comparison of the three charge controllers listed above. Note that in this comparison, special attention was given to the quiescent current ($I_Q$) of the regulators, as this determines to a great deal the efficiency of the entire system.

<table>
<thead>
<tr>
<th>Device</th>
<th>Internal reg.</th>
<th>MPPT</th>
<th>$I_Q$</th>
<th>Ext. part cnt.</th>
<th>Availability</th>
<th>Solderability</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX17710</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BQ25504</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LTC3105</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>o</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

As can be seen from the table, the MAX17710 has a score of +1, the BQ25504 has -1 and the LPC3105 has 0. As such, the MAX17710 was selected to be the charge controller of choice for this design.

**Linear voltage regulator**

Since the chosen charge controller has a built in voltage regulator, it was not necessary to look into using external regulators. While some of the regulators mentioned in section 5.2.2 are better than the voltage regulator in the MAX17710 in terms of quiescent current, it was decided that for complexity reasons no external voltage regulator would be used.

**Status & control signal processing**

While the MAX17710 has several control signals, none of them are of any use for the system. The control systems are only used to select the internal voltage regulator output voltage, which has to be fixed at 3.3 V for correct operation, and for turning the internal voltage regulator on or off and switching its power mode, which has to be fixed to high current mode to correctly supply the systems with energy at all times.
5.1.3 Designed circuit

Now that the defining components have been selected, a circuit could be designed. The final circuit for the charge controller is shown in figure 5.2.

The solar cell and the battery are connected to header P2, with a common negative terminal on pin 2 of this connector. Pin 1 is the positive terminal of the battery, pin 3 is the positive terminal of the solar cell.

The solar cell is placed in series with C11, a 10 µF electrolytic capacitor. This capacitor is required for the boost converter in the MAX17710 for dealing with the oscillating currents, which the solar panel would otherwise not be able to handle efficiently. According to the MAX17710 datasheet, [26, pp. 11], this capacitor must be at least 70 times larger than the CHG pin capacitor (C7). Also, the capacitor should be no larger than 47 µF to keep leakage currents low, though larger capacitances are stated to increase boost converter efficiency. 10 µF was chosen because of the it was found that the leakage currents are indeed quite significant (3 µA, [29]) for higher capacities and because it is a very common capacity value and this cheap and easy to procure.

The filter and voltage divider formed by C12 and R4-R6 is designed to decrease the voltage from the solar panel by a factor of three while not dividing transient behavior of this voltage. This is required as the charge controller is configured to turn on when the voltage on the FB pin exceeds 1 V, while the operating voltage of the selected solar panel is approximately 3 V. The capacitance and resistance values were chosen according to the datasheet [26, pp. 11-12]. Two 1 MΩ resistors placed in parallel were used in stead of a single 500 kΩ resistor to save costs for small series, as such resistors are usually sold at minimum order quantities of 100, and it is thus beneficial to use three 1 MΩ resistors over using two different values.

To be able to read diagnostic information from the charge controller circuit, the FB pin voltage was also connected to an analog-to-digital converter pin on the microcontroller in the control block of the system. Since this pin is not expected to ever exceed 3.3 V, no additional circuitry is required to do this.

The boost inductor, L1, was chosen to be 10 µH, as only an absolute minimum value of 0.85 µH was given in the MAX17710 datasheet to ensure that the LX pin currents do not exceed the absolute maximum ratings [26, pp. 11]. Since size is not of importance in this design, a much larger inductor could be chosen.

The boost converter diode, D1, was chosen as such because this part was recommended in the MAX17710 datasheet [26, pp. 11].

A 100 nF capacitor was used for the CHG pin capacitor as this was the minimum value and it was bounded upwards by having to be 70 times smaller than C11, and 100 nF capacitors were already
used in other parts of the circuit.

The capacitors for the REG and PCKP pins, C8 and C6 respectively, were chosen because these values were used in the block diagram on page 8 of [26].

SEL1 was left open to select 3.3 V for the voltage regulator output voltage. SEL2 was tied to GND as this was shown in all example circuits in the datasheet. LCE and AE were both tied to the battery voltage to select high current voltage regulator operation.

S2 and S3 are solder jumpers on the PCB (they are just a 0402 surface-mount resistor footprint which may be shorted using a solder bridge) used to select or completely disconnect the charge controller. This was done to allow switching between the energy harvesting based concept and the pure energy storage concept as described in the next section.

Since it is a requirement to be able to measure when the battery is nearing depletion, a method for measuring the battery voltage was also required. The circuit designed for this purpose is shown in figure 5.3.

In this circuit, R8 and R9 are used to convert the battery voltage, which may be as high as 4.2 V, down to 3.3 V in a 2:1 ratio. The resistances were chosen to be low enough to allow proper operation of the analog-to-digital converter (built-in in the microcontroller used) which it connects to, yet high enough to keep measuring currents as low as possible. However, as the current would still be $4.2 \text{ V} / 200 \text{ kΩ} = 21 \mu\text{A}$, a shutdown circuit was required to not generate excessive battery currents while the system is sleeping.

This shutdown system is implemented by means of a high-side switch, using a BSS84 PMOS transistor. While a low-side switch would be easier to implement, this would cause the analog-to-digital pin voltage to rise to the battery voltage, which is exactly what this divider is trying to prevent. The BSS84 transistor was used because simulation models were available in the free SPICE simulator LTspice by Linear Technology and because they were widely available – any general purpose logic-level PMOS transistor should do.

Since the gate of this transistor still has to be driven by a voltage of up to 4.2 V with reference to the GND, it cannot be driven directly by the microcontroller. This is what R7 and Q2 are for. When PWR_BAT_EN is low, Q2 is turned off, and R7 pulls the gate of Q1 to the battery voltage, turning off the voltage divider. When PWR_BAT_EN is raised above the gate trigger voltage of Q2, it pulls the voltage on the gate of Q1 to the GND, turning it on and the voltage divider on. Since the gate trigger voltage of the BSS123 is lower than 3.3 V [30], the gate can be driven directly by the microcontroller. Note that the BSS123 was chosen for the same reasons as the BSS84, and the value of R7 was chosen to be 100 kΩ as this value is already in use for R8 and R9.

Note that the datasheets for the transistors, [30, 31], only state a maximum leakage current of 1 μA. This was actually found to be quite common, which is why the circuit was simulated using LTspice. The result of the simulation was that only about 21 pA would be used by the circuit for a battery voltage of 4.2 V when off. Although, from the author’s experience, the models in LTspice
often give much better results than real life implementations of the same circuit, such a result of several orders of magnitudes smaller than the maximum value of 1 µA given in the datasheet likely only means that Fairchild Semiconductor has not performed large-scale tests to determine the leakage current, and as such, the transistors will probably perform much better than this.

5.2 Implementation of the pure energy storage system

The second concept which was selected is the pure energy storage solution with just a linear voltage regulator. The design of this concept is presented in this section.

5.2.1 Functional block diagram

As with the previous design, the first thing which was to be done was the creation of a block diagram. The resulting block diagram is shown in figure 5.4.

![Block diagram for the pure energy storage concept](image)

Figure 5.4: Block diagram for the pure energy storage concept

From the subsystems in this block diagram, only the linear voltage regulator and possibly interfacing circuitry for any status and control signals need to be selected and implemented. The next section describes how these components were chosen.

5.2.2 Component selection

This section describes the selection process for the linear voltage regulator and the interfacing circuitry, in that order.

### Linear voltage regulator

For the selection of the linear voltage regulator, four devices were compared. These devices are the TPS78233DDCT by Texas Instruments [23], the ADP162AUJZ-3.3 by Analog Devices [32], the MCP1700T-3302E/MB by Microchip [33] and the XC6215B332NR by Torex [34]. These are the regulators with the lowest quiescent current meeting the output current requirements for each of the researched manufacturers, at the time of writing.

As linear voltage regulators are very generic, the features of each of the regulators which are the primary concerns in this design can best be presented in a table (5.2).

<table>
<thead>
<tr>
<th>Device</th>
<th>Price</th>
<th>Output cap.</th>
<th>Package</th>
<th>$I_O$ [nA]</th>
<th>$V_{DO}$ [mV]</th>
<th>$I_O$ [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPS78233DDCT</td>
<td>€1.31</td>
<td>1 µF ceramic</td>
<td>TSOT23-5</td>
<td>500</td>
<td>130</td>
<td>150</td>
</tr>
<tr>
<td>ADP162AUJZ-3.3</td>
<td>€0.60</td>
<td>1 µF ceramic</td>
<td>TSOT23-5</td>
<td>560</td>
<td>195</td>
<td>150</td>
</tr>
<tr>
<td>MCP1700T-3302E</td>
<td>€0.49</td>
<td>1 µF ceramic</td>
<td>SOT-89</td>
<td>1600</td>
<td>178</td>
<td>250</td>
</tr>
<tr>
<td>XC6215B332NR</td>
<td>€0.72</td>
<td>100 nF ceramic</td>
<td>SSOT-24</td>
<td>1000</td>
<td>420</td>
<td>200</td>
</tr>
</tbody>
</table>

The prices listed in the table are the per-unit prices at Farnell at the time of writing and are only listed for comparison purposes.
The output cap. column lists the output capacitor which the voltage regulators require for stability, where a smaller capacitor is obviously better because they are smaller and typically have a lower leakage current.

The package column lists the selected packaging option for each of the voltage regulators. All of the packages are comparable leaded surface-mount types.

The values listed in the $I_Q$ (quiescent current) and $V_{DO}$ (dropout voltage) columns are typical values. The $I_O$ column lists the maximum output current for each regulator.

It was now relatively straightforward to select between the voltage regulators. The comparison is listed in table 5.3.

<table>
<thead>
<tr>
<th>Device</th>
<th>Price</th>
<th>Output cap.</th>
<th>$I_Q$ [nA]</th>
<th>$V_{DO}$ [mv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPS78233DDCT</td>
<td>-</td>
<td>o</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>ADP162AUJZ-3.3</td>
<td>o</td>
<td>o</td>
<td>++</td>
<td>o</td>
</tr>
<tr>
<td>MCP1700T-3302E</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>+</td>
</tr>
<tr>
<td>XC6215B332NR</td>
<td>o</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

It is clear that, while it is the most expensive option, the TPS78233DDCT is the best candidate for this design.

Status & control signal processing

Since the TPS78233DDCT does not have any control signals other than an enable signal, no status or control signals have to be connected to the control unit. As such, no additional circuitry is required.

5.2.3 Designed circuit

It is now very straightforward to implement the circuit for the voltage regulator, as the main part of this circuit is simply the one defined in the datasheet. The circuit is shown in figure 5.5.

![Figure 5.5: Pure energy storage circuit](image)

In this circuit, C9 serves as the input filter capacitor for the regulator, and C10 does the same for the output. The capacitance (1 $\mu$F) and technology (ceramic) for these capacitors are shown in the figure on page 11 of [23].

S4 and S5 are solder jumpers on the PCB (they are just a 0402 surface-mount resistor footprint which may be shorted using a solder bridge) used to select or completely disconnect the linear voltage regulator. This was done to allow switching between the pure energy storage concept and the energy harvesting based concept as described in the previous section.
Chapter 6

Performance measurements and battery scaling

As became clear in section 4.1, it was found to be very difficult to model the current consumption of the system accurately, because the duty cycle $\delta$ was unknown. Therefore, a prototype of the system had to be created, and the current consumption had to be measured.

This chapter describes this process of testing the performance of the prototype and determining the required battery capacity accordingly. In section 6.1, the performance of the pure energy storage system is measured and the battery capacity required is determined. In section 6.2 the optional harvesting system is also taken into account.

6.1 Current consumption measurements

To determine the power, or rather, current requirements for the sensor, two quantities were measured: the charge in coulombs required to take a measurement and transmit the acquired data, and the quiescent current of the system. The minimum battery capacity without harvesting may then be calculated as follows.

$$Q_{bat,\text{min}} = I_q T_{operate} + Q_{meas} \lfloor f_s T_{operate} \rfloor \approx (I_q + Q_{meas} f_s) T_{operate}$$

In this equation, $Q_{bat,\text{min}}$ is the minimum battery capacity in Coulombs required to run the system for $T_{operate}$ seconds. $I_q$ is the measured quiescent current of the sensor, $Q_{meas}$ is the measured charge required for a sample, and $f_s$ is the sample rate of the sensor.

$Q_{meas}$ will be determined by measuring the current as a function of time, and then applying the following equation.

$$Q_{meas} = \int i(t) - I_q dt$$

In this equation, $i(t)$ represents the measured current.

6.1.1 Charge required per measurement

As can be seen from equation 6.2, the charge required is calculated by integrating the battery current over time. To measure this current as a function of time, a BitScope BS120 oscilloscope was used, connected to a shunt resistor in the low side of the battery supply lines. As the BS120 is relatively inaccurate, the results were verified using an Agilent DSO6034A oscilloscope. The reason for using the BS120 in the first place, was because it turned out to be rather difficult and costly to connect the DSO6034A to a computer to read the raw measurement data from it.

As stated, a shunt resistor is used to measure the current indirectly, as oscilloscopes measure voltages. The maximum value for this resistor is determined by the minimum and maximum operating voltages of the sensor, or, in other words, the minimum and maximum battery voltages which the
Figure 6.1: Circuit for measuring the active current as a function of time

sensor is expected to operate with. This is because the input voltage will otherwise be too high under a no-load condition or too low when the maximum expected battery current is flowing.

This maximum value for the resistor may be calculated as follows.

\[ R_{sh,\text{max}} = \frac{U_{\text{bat,max}} - U_{\text{bat,min}}}{I_{\text{bat,max}}} \]  

(6.3)

In this equation, \( R_{sh,\text{max}} \) is the maximum shunt resistance, \( U_{\text{bat,min}} \) and \( U_{\text{bat,max}} \) are respectively the minimum and maximum expected battery voltages and \( I_{\text{bat,max}} \) is the maximum expected battery current. It is assumed that the supply voltage is set to \( U_{\text{bat,max}} \). Using a shunt resistor of the value given by this formula, the supply voltage of the sensor module will drop to \( U_{\text{bat,min}} \) when the current equals \( I_{\text{bat,max}} \). Using 3.7 V as a minimum voltage to be on the safe side and 50 mA for \( I_{\text{bat,max}} \), \( R_{sh,\text{max}} = 10 \ \Omega \).

As no minimum is defined for the resistance as long as the voltage drop is still measurable, however, the value was chosen to be slightly lower, still. As can be seen in figure 6.1, the value was chosen to be 4.7 \( \Omega \).

The measurements were finally taken by setting up the sensor to take a sample and transmit it approximately every two seconds. The oscilloscopes were set to trigger on a rising edge at approximately 50 mV. The time reference was set to 25\% to also sample the current when the sensor is still turning on. The total sampling time was set to be 400 ms.

In total, 4740 data sets of 1000 samples each were taken. The mean of all these measurements was computed, and was finally offset corrected using the mean of the first and last 50 ms of each reading. The resulting data is shown in figure 6.2.

The integral may now also be computed, by calculating the area under the graph in figure 6.2. This value was determined to be 0.90 mC.

### 6.1.2 Quiescent current

As seen in equation 6.1, the quiescent current of the system must also be determined. This was done in a much less technical way: the current was simply measured with a multimeter. The full circuit is shown in figure 6.3.
Figure 6.2: Mean measured supply current when a measurement is taken

Figure 6.3: Circuit for measuring the quiescent current

As can be seen in the figure, an Agilent 34401A multimeter was used. It was set to its maximum accuracy and autoranging was turned on. With this setup, the least significant digit expresses tenths of microamperes. Measuring the quiescent current was done tentatively by noting down the displayed current when the reading stabilizes.

Since both the harvesting based and pure energy storage concepts will logically give different results, both these concepts were to be measured. Additionally, while debugging, it was found that the internal voltage regulator of the MAX17710 energy harvester was highly inaccurate. To still be able to use the energy harvesting portion of this integrated circuit reliably, a TPS78233 was used for both versions. This however means that the quiescent current of this system is considerably higher than that of either of the two concepts, as two voltage regulators were now running at the same time. The current of this setup was also to be measured.

Unfortunately, more complications arose. The circuit board used for the pure energy storage concept at some point started behaving strangely – the current went up by approximately 80 - 120 uA for an as of yet unknown reason. The exact quiescent current consumption of this concept was unfortunately never written down before the anomaly occurred. From memory, however, it was approximately 6 uA.

Luckily, the circuit board used to test the energy harvesting concept was still operational, and a more validated measurement was taken for this board. It was found to be 8.7 uA. No measurement of the energy harvesting system without the secondary voltage regulator or with the internal regulator of the MAX17710 disabled were taken before the release of this revision, primarily due to time...
constraints, but also due to the fact that the risk of tampering with the only functional circuit board was deemed too high.

6.1.3 Required battery capacity

It is now possible to compute the minimum battery capacity which conforms to the requirements set in the appendix using equation 6.1 as a function of the required sample rate and operational time. For the calculation, the quiescent current measurement for the energy harvesting based circuit board was used, as the other measurements were relatively unreliable. Filling in equation 6.1 with the measured data, the following result is found.

\[ Q_{\text{bat,min}} \approx (8.7 \mu A + 0.90 mC f_s) T_{\text{operate}} = 8.7 \cdot 10^{-6} T_{\text{operate}} + 9.0 \cdot 10^{-4} f_s T_{\text{operate}} \quad (6.4) \]

As stated in [4] and [5], \( f_s \) was set to 1/20 Hz. Note that this is three times as fast as the speed stated in the requirements, this was done due to restrictions in the ZigBee protocol. From the appendix, it can be found that minimum operational time \( T_{\text{operate}} \) was set to one year, or \( 3.15 \cdot 10^7 \) seconds. Filling in these numbers, a minimum capacity of 1686.2 C is obtained. Converted to mAh, the unit most commonly used to indicate battery capacity, this equals a minimum capacity of 468 mAh.

However, recall that in section 4.5.2 it was stated that the voltage of a lithium-ion polymer battery drops below operational levels for this power management system at approximately 90 % depletion. This means that the capacity computed above is only 90 % of the required capacity, thus, the new minimum required capacity equals 520 mAh.

Finally, self-discharge currents are to be taken into account. As stated in section 3.3.1, the self-discharge currents amount to approximately 5% of their capacity per month. This means that, in those 12 months, 60% of the capacity is wasted, and therefore, the previous number amounts to only 40 % of the actual required capacity. This means that a 1300 mAh lithium-ion polymer battery is required.

6.2 Solar panel and energy harvester performance

Now that the minimum battery capacity for the pure energy storage concept is computed, the only remaining question was now how much smaller the battery may be when the energy harvesting system is used. For this, the average charging current of this system was to be determined. The measurements were taken under office light conditions.

This current was measured in the same way as the quiescent current, only with the solar panel connected. This is depicted in figure 6.4.

![Figure 6.4: Circuit for measuring the charging current of the energy harvesting system](image)

The measurements found will obviously vary among specific light conditions. The current was found to be approximately 110 \( \mu A \) near a window at dusk with the fluorescent lights of the room switched on. During the day, measurements up to about 300 \( \mu A \) were seen.
For simplicity, it is assumed that these lighting conditions are in effect ten hours per day on average. In the remaining fourteen hours, the charge current is assumed to be zero. This amounts to an average charge current of 45 μA.

It should be noted that this figure includes the quiescent current of the system. Therefore, the equation for measuring the minimum battery capacity is now as follows.

\[
Q_{bat, \text{min, harvest}} \approx (Q_{\text{meas}} f_s - I_{ch}) T_{\text{operate}}
\]  

In this equation, \( I_{ch} \) is the average charging current estimated above. Filling in this equation with the same \( Q_{\text{meas}}, f_s \) and \( T_{\text{operate}} \) as was used for the pure energy storage concept, it is found that the required battery capacity, neglecting low-battery-voltage and self-discharge losses, equals -7.32 C. This negative capacity indicates that, under these lighting conditions and with an ideal battery, the solar panel is capable of supplying the system with power indefinitely.

Unfortunately, the battery is not ideal, invalidating the above computation. Also, a battery would still be required to supply the system with power at night or when the light is simply off. By filling the assumed fourteen hours of darkness per day into equation 6.1, a capacity of 2.69 C, or 0.822 mAh was obtained.

As before, the battery losses need to be accounted for. The first loss was the 90% discharge limit due to the voltage regulator, raising the 0.822 mAh to 0.912 mAh. Self discharge should also be taken into account for the timespan of a day, which would amount to the almost negligible 0.17% of the capacity, increasing the required battery capacity to 0.914 mAh.

Whether a battery of this capacity can be used however, all comes down to whether the harvesting system is indeed capable of fully recharging the battery in the ten hours of light. This may be computed using equation 6.5, using the nominal charge current under office light conditions in stead of the daily average, however. If this value amounts to negative the battery capacity computed above or less, this is the case. Unfortunately, this charge was determined to be only -0.652 mAh.

Still, the required battery capacity may now be computed. The difference between the two numbers equals the charge lost daily, assuming for the self-discharge losses however a battery capacity of only 0.914 mAh. If these largely incorrectly estimated self-discharge are ignored for now and only added to the result in the end however, this problem can be circumvented to a certain degree. Therefore, 0.912 - 0.652 = 0.260 mAh is lost daily. The total required battery capacity to run the system for a year, neglecting self-discharge losses, is then 92.6 mAh, plus an additional 0.260 mAh to make it through the last day, thus amounting to 92.8 mAh.

As stated, the self-discharge losses for that year now still need to be applied. These were previously calculated to be approximately 60% . Therefore, the required battery capacity for the system is 213 mAh.

Note that this capacity is only 17.8% of the battery capacity which would be required without the harvesting system, thus, the harvesting system is certainly significant.
Chapter 7

Conclusion, recommendations and future work

This chapter provides the conclusion of the design of the energy system of the designed sensor (7.1), as well as recommendations for the use of the design (7.2) and possible future work (7.3).

7.1 Conclusion

While the energy management system works and the optional energy harvesting system was indeed found to be significant, the system suffers from a number of serious flaws.

The most serious of these flaws is that one out of the two manufactured prototype boards has failed, in the sense that it now uses approximately 100 µA more battery current than the other board. Thus, there may be significant problems with the circuit or the circuit board.

Another important flaw in the system is that the Xbee module has thus far been unable to receive data from the computer reliably. As such, no commands or update rate changes can be given to the sensor wirelessly, and the less convenient implementation of using a jumper to switch between demonstrator and normal mode was used. This flaw is likely attributable to the fact that the voltage regulator may not provide a stable enough output voltage.

Still, assuming the system does not fail within a year after it has been commissioned, the energy system was found to be sufficiently efficient to meet the one year on-time requirement without service, without the need for an unrealistically big battery. Additionally, the energy harvesting system was successful in significantly reducing the battery size required to run the system for a certain amount of time, even though the on-chip regulator on this chip was insufficiently accurate and had to be replaced with a second regulator, decreasing the efficiency.

In short, the current system functions to a certain degree, but future work is required to make the sensor ready to be put into service.

7.2 Recommendations

It is recommended that the client does further research into the problems found with the current circuit board before using the system as a demonstrator. This is because the current version seems to not be reliable enough to be used as such.

7.3 Future work

This section lists some examples of future work which may be done relating to this subject.

**Battery selection** Due to the difficulties encountered with the testing of the prototype, there was insufficient time to select a battery for the sensor module. This should still be done for the system to be useful.
**Debugging**  At the time of writing, the sensor module is not yet fully completed, due to the numerous problems with the prototype and the lack of a battery. It is recommended to do further research into the cause of these problems, and to design and produce a second revision of the circuit board.

**Dye-sensitized solar cells**  While selecting an energy harvesting system, as described in section 4.3, it was found that using the relatively new technology of dye-sensitized solar cells (DSSC) would result in much greater energy harvesting power than with the amorphous solar cell which was used in this design. The reason for not choosing a DSSC was mainly to do with the lack of commercial availability of these cells at the time. As such, it is suggested that, when these cells do become available, the design be modified for the use of a DSSC.

**Design of the charge controller**  In the implemented design which used energy harvesting, an off-the-shelf charge controller was used to charge the battery. It is suggested that, in future work, this charge controller is also designed. When this is done, it would be possible to optimize the design for the used solar cell and battery. Also this approach could allow for more control in building and testing the design.
Bibliography


Appendix: Program of Requirements

Note: the following appendix applies to the complete sensor system, not just the energy system presented in this thesis. See chapter 2 for more information.

The required product is a wireless indoor climate sensing system. It is an autonomous sensor that transmits several parameters about its environment wirelessly. The product will be used to demonstrate a set of energy efficient sensors, which are developed at the Electronic Instrumentation department at Delft University of Technology. This document lists all requirements and wishes as stated by the client.

In the requirements below, the following definitions apply.

1. **Sensor** - the sensor module to be designed.
2. **Host** - the system which the sensor communicates its data to.
3. **Sampling rate** - the rate at which the sensor takes sensor value samples.
4. **Transmission rate** - the rate at which the sensor transmits (previously recorded) sensor data.

1 Usage Requirements

[1.1] The product must measure at least temperature and humidity. More measured quantities are encouraged.

[1.2] All communications between the sensor and the host must be done wirelessly.

[1.3] The product must function autonomously in terms of energy supply.

[1.4] If a battery is used, the user should be notified when the battery needs to be replaced.

[1.5] The measured quantities should be visible on a computer.

2 Requirements according to the ecological situation of the system’s environment

[2.1] The product must function indoors.

[2.2] The transmitter frequency, bandwidth and output power must fall within Dutch regulations.

[2.3] The product must be non-intrusive within its operating environment, i.e. it should not draw attention to itself.
3 System Requirements

[3.1] If a battery is used, the sensor must operate without battery replacement for at least a year. This requirement assumes the sensor is run in normal (not demo) mode.

[3.2] The range for wireless communication must be at least 5 meters.

[3.3] The sensor must have at least two operating modes in terms of sampling rate and transmission rate: a demo mode and a normal mode. In demo mode, the sample and transmission rate must be at least once per second. In normal mode, the sample and transmission rate must be at least once per minute.

[3.4] The operating mode must at least be selectable using a jumper or switch on the sensor. Being able to set the operating mode wirelessly is a nice to have. Being able to set more sampling and transmission rates is also a nice to have.

[3.5] Having the possibility to set minima and maxima for the measured quantities is a nice to have. If such a limit were to be exceeded, the sensor should wirelessly transmit the current sensor data regardless of transmission rate.

[3.6] To measure the temperature and humidity, the sensor chip developed by the Electronic Instrumentation department at Delft University of Technology and produced by NXP must be used.

[3.7] The chip mentioned above must be visible and influenceable during a demonstration. For instance, it must be possible to breathe on or touch the sensor to demonstrate that the measured quantities indeed change on the screen in such a case.

[3.8] The system must deliver the measured data in such a way that does not reduce the accuracy of the sensor chip(s) used.

4 Installation Requirements

[4.1] It must be possible to install the product without changes to the environment.

[4.2] The installation must be as simple as inserting a battery and installing some software on a computer. In other words, it should be “Plug & Play”. It is acceptable if something like a USB dongle is required for communications.

[4.3] Replacing a battery must be possible within a minute.

5 Project Requirements

[5.1] All software written for this product must be well documented.

[5.2] All hardware designed for this product (circuits and circuit board layout) must be well documented.

[5.3] Writing platform independent software is encouraged. The ”platform” is defined here as being the operating system for PC based software and the microcontroller (architecture) used for hardware based software/firmware.
### Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>a-Si</td>
<td>Amorphous silicon solar panel.</td>
</tr>
<tr>
<td>AA(A) battery</td>
<td>Standard dimensions for batteries commonly used in household equipment.</td>
</tr>
<tr>
<td>c-Si</td>
<td>Crystalline silicon solar panel.</td>
</tr>
<tr>
<td>Charge controller</td>
<td>An energy conditioning system designed specifically to charge a certain type of battery or another type of energy storage.</td>
</tr>
<tr>
<td>(Charge) cycle life</td>
<td>The amount of times a battery can be discharged and recharged before its capacity starts to decrease considerably due to wear.</td>
</tr>
<tr>
<td>Control unit</td>
<td>The main control unit in the sensor module, defined to be an LPC1114 in [4].</td>
</tr>
<tr>
<td>DSSC</td>
<td>Dye-sensitized solar cell.</td>
</tr>
<tr>
<td>Energy harvesting/scavenging</td>
<td>The process of extracting energy from the environment. See also section 3.2.</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>Lithium-ion battery.</td>
</tr>
<tr>
<td>LiPo</td>
<td>Lithium-ion polymer battery.</td>
</tr>
<tr>
<td>MIST1431</td>
<td>The sensor chip developed by the Electronic Instrumentation department of the TU Delft and NXP, which the designed system is to be a demonstrator for.</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nickel metal-hydride battery.</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed circuit board.</td>
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<tr>
<td>RF</td>
<td>Radio frequency.</td>
</tr>
<tr>
<td>Self-discharge rate</td>
<td>The rate at which a battery or capacitor discharges itself due to leakage currents. Usually specified as a percentage per unit of time.</td>
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