Examensarbete utfört i Elektroniska kretsar och system vid Tekniska högskolan vid Linköpings universitet av

Björn Holby och Carl-Fredrik Tengberg

LiTH-ISY-EX-ET–15/0437–SE

Linköping 2015
Low Power Current Sensing Node Powered by Harvested Stray Electric Field Energy

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Handledare: Peter Johansson
ISY, Linköpings universitet

Examinator: Dr. J Jacob Wikner
ISY, Linköpings universitet

Linköping, 25 maj 2015
Title: Low Power Current Sensing Node Powered by Harvested Stray Electric Field Energy

Abstract:
In this thesis, the possibility of harvesting energy from a multicore power cable connected to a power outlet is presented and evaluated. By surrounding a power cable with a conductive material connected to ground, it is shown that the difference in potential between the power cable and the conductive material causes a capacitance which can charge a capacitor that in combination with an energy management circuit can be used to wirelessly transmit data with an interval depending on factors like the length of the surrounding material and the type of cable it is placed around. In addition to this, a technique to, in a non-invasive way, sense whether there is alternating current flowing in a multicore power cable is brought up. The results show that this technique can be used to detect alternating current without having a device connected between the power cable and the power outlet. These two sections combined are used to design a surveillance system that should monitor consumer electronics in the home environment where there is a fire hazard. The system should send out a warning signal that is visible for the homeowner to remind the user to switch off the power of the electronic devices before leaving home.

Keywords: Energy harvesting, low power, sensor node, wireless communication
Sammanfattning

I detta examensarbete undersöks möjligheterna att utvinna energi från en strömkabel med flera ledare kopplat till ett 230 V AC vägguttag. Genom att klä in kabeln i ett ledande material har det visat sig att potentialskillnaden mellan strömkabeln och det jordade, omkringliggande materialet kan användas för att kapacitivt ladda upp en kondensator som med hjälp av en hanteringskrets trådlöst kan överföra data med jämna mellanrum beroende på faktorer som längden av det kringliggande materialet och typ av strömkabel. Utöver detta utvärderas även en teknik som ska kunna detektera växelström i en strömkabel med flera ledare utan att koppla någonting mellan strömkabeln och vägguttaget. Denna teknik visade sig fungera, om än med utrymme för förbättring. Dessa två delar är tillsammans tänkta att utgöra ett övervakningssystem för brandfarlig hemelektronik där en varningssignal ska skickas från en trådlös sensor-nod till en mottagare som ska varna om man skulle lämna hemmet med brandfarlig elektronik påslagen.
Abstract

In this thesis, the possibility of harvesting energy from a multicore power cable connected to a power outlet is presented and evaluated. By surrounding a power cable with a conductive material connected to ground, it is shown that the difference in potential between the power cable and the conductive material causes a capacitance which can charge a capacitor that in combination with an energy management circuit can be used to wirelessly transmit data with an interval depending on factors like the length of the surrounding material and the type of cable it is placed around. In addition to this, a technique to, in a non-invasive way, sense whether there is alternating current flowing in a multicore power cable is brought up. The results show that this technique can be used to detect alternating current without having a device connected between the power cable and the power outlet. These two sections combined are used to design a surveillance system that should monitor consumer electronics in the home environment where there is a fire hazard. The system should send out a warning signal that is visible for the homeowner to remind the user to switch off the power of the electronic devices before leaving home.
Acknowledgments

We would like to thank Syntronic.

Linköping, May 2015
Björn Holby och Carl-Fredrik Tengberg
1 Introduction 1
1.1 Background ........................................ 1
1.2 Thesis scope ..................................... 2

2 Theoretical background 3
2.1 Related work .................................... 3
2.2 Energy harvesting ................................. 5
2.3 The electromagnetic field ......................... 6
2.4 Capacitor ........................................ 7
   2.4.1 Expression for storage capacitor .......... 7
2.5 Operational amplifier ............................. 9
   2.5.1 High-pass filter ............................. 11
   2.5.2 Low-pass filter ............................. 13
2.6 Multicore cables ................................ 14
2.7 Linear hall effect sensor ......................... 15
2.8 Analog to digital conversion ..................... 15
2.9 Serial Peripheral Interface ....................... 15
2.10 ShockBurst™ mode ............................... 16
   2.10.1 ShockBurst™ TX ............................ 16
   2.10.2 ShockBurst™ RX ............................ 16

3 Method ........................................... 17
3.1 Getting an overview of the system ................ 17
3.2 Energy harvesting circuit ......................... 19
   3.2.1 Simulation of the harvesting circuit ..... 21
   3.2.2 Voltage regulators ......................... 22
3.3 Wireless data transmission node ................. 23
   3.3.1 Components ................................ 23
      3.3.1.1 RF transceiver ....................... 23
      3.3.1.2 Microcontroller ....................... 23
   3.3.2 Using the microcontroller with the RF-transceiver 24
5.1.3 Different cables ........................................... 67
5.1.4 Dynamic current consumption .......................... 68
5.1.5 Placement of the hall effect sensors .................... 68
5.2 Discussion regarding the method .......................... 68
5.3 Conclusions .................................................... 69
5.4 Future work ................................................... 69
  5.4.1 Improving the energy harvesting circuit ............... 69
  5.4.2 Alternative power source ............................... 70
  5.4.3 Multi sensor node system .............................. 70
  5.4.4 Improved receiver ..................................... 71

A Code transmitter .............................................. 75
B Code receiver .................................................. 81

Bibliography ..................................................... 85
List of Figures .................................................. 88
List of Tables ................................................... 90
<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-To-Digital Converter</td>
</tr>
<tr>
<td>AM</td>
<td>Address Match</td>
</tr>
<tr>
<td>CD</td>
<td>Carry Detect</td>
</tr>
<tr>
<td>CE</td>
<td>Chip Enable</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
</tr>
<tr>
<td>CSN</td>
<td>SPI Chip Select Not</td>
</tr>
<tr>
<td>DR</td>
<td>Data Ready</td>
</tr>
<tr>
<td>EEPROM</td>
<td>Electrically Erasable Programmable Read-Only Memory</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>I/O</td>
<td>Input / Output</td>
</tr>
<tr>
<td>LED</td>
<td>Light-Emitting Diode</td>
</tr>
<tr>
<td>PWR</td>
<td>Power</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio-frequency identification</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
</tr>
<tr>
<td>TX_EN</td>
<td>Transmit Enable</td>
</tr>
<tr>
<td>VCC</td>
<td>Supply Voltage</td>
</tr>
</tbody>
</table>
1.1 Background

Today, embedded electronic systems are used in every imaginable situation such as monitoring traffic situations, sensing changes in temperature, supervising and controlling some part of a larger system etc. The elevator in an apartment building and even the electric toothbrush are examples of embedded systems. The bottom line is, embedded systems exist everywhere. When developing these embedded electronic systems, many parameters come into play. The system might have to perform in harsh environments and get exposed to humidity, warm/cold temperatures and at the same time be able to produce accurate results with short reaction time as well as being small in physical size and have a low power consumption.

As a wireless system with the main task of monitoring the occurrence of some events in areas that are hard to get reach, a desirable feature is to keep the maintenance frequency as low as possible. One significant factor is the power consumption of the sensor node and it is desirable not to have to replace the battery of the sensor node more often than needed [24]. In recent years, a lot of research has been made in the field of energy harvesting in order to find alternative sources of energy to power, low-power wireless sensor nodes with the ultimate goal of being able to replace the battery and harvest energy from the environment that the sensor node is placed in [24]. Having a sensor node which can run solely on harvested energy from its surroundings, the lifetime and maintenance frequency of the sensor node would only be determined by the actual components and removing the existing, finite, battery as the power supply from the equation.
Over the last ten years in Sweden alone, the fire brigade has had an average of 25800 call-outs a year, 10600 of them being fires in buildings. In the year 2014, there were 5583 fires in Swedish homes. The most common reason for these fires by far is stoves left turned on [13].

The goal with this project is to design a surveillance system which should monitor fire hazardous consumer electronics in the home environment that should warn the homeowner if he or she is about to leave home with such a device still turned on. In this thesis, a new and innovative method is designed, tested and evaluated towards solving this.

1.2 Thesis scope

Our aim with this thesis is to design a prototype of an application which in a non-invasive way is able to detect current flowing in 230 V AC power cables. The status of the current flowing in the cable should get sent from a wireless sensor node to a receiving base station where the status code can be read.

In order to achieve this, our thesis will raise the following questions:

- Is it possible to detect current flowing through a multicore power cable connected to a 230 V AC outlet in a non-invasive way?
- How much energy would be required to power the above-mentioned wireless sensor node?
- How can this required energy be harvested from a multicore power cable connected to a 230 V AC outlet?

In this thesis, an energy harvesting method is brought up and analyzed to whether this energy alone can act as a power supply for the system.
2.1 Related work

When designing a sensor network where the sensor nodes task are to monitor some events such as current or voltage monitoring, vibration sensing, temperature sensing etc., it is often the case that the sensor nodes are placed in environments that can be hard to reach if service maintenance would be required. Since engineers are striving to design sensor nodes which require as little maintenance as possible, one desirable feature is a long life length of the power supply. This has opened up a field of research that is investigating different methods of energy harvesting, which is the technique where the ambient energy in the surrounding environment is collected and used to power large or small scale electronics, with the ultimate goal of replacing the battery as its source of power.

In a survey[16], different methods such as vibration, thermal, solar, magnetic field and electric field energy harvesting were presented. As well as the energy harvesting methods, different products used for each method combined with an evaluation of their efficiency is described.

By placing a piezoelectric material inside of a shoe, the average power emitted from a walking person when putting weight on the same shoe with a frequency of 0.9 Hz was about 1.3 mW. When placing a flexible, multilaminar polyvinylidene-fluoride (PVDF) bimorph stave in the area between the middle of the foot and up till the front of the foot, and when placing a prestressed spring metal strips laminated with a semi-flexible form of piezoelectric lead zirconate titanate (PZT), the average power was 8.4 mW [23]. The harvested energy from a person walking was used to power an RFID system which could transmit a signal every two seconds[23].
It has been shown that by surrounding a multicore cable with a conducting material, such as aluminum foil [4] or copper tape [15], energy can be harvested from the electric stray field of a regular multicore power cable connected to a power outlet [4]. The stray capacitance introduced due to the difference in potential will cause the conducting material to accumulate electric charge which can be rectified and stored in a capacitor [4]. Results showed [4] that the rate of charge accumulated in the storage capacitor makes it possible to read a sensor value and wirelessly transmit the data every 42 seconds. The same authors later on edited the design for their energy harvesting circuit by introducing an MEMS-switch which greatly simplified the circuit [15].
2.2 Energy harvesting

The concept of energy harvesting is to make use of the ambient energy existing in the surrounding environment. Some classical examples of sources for energy harvesting are sunlight and wind, which today are already used in a large scale. Energy harvested from these sources are capable of generating large quantities of power in the range of several megawatts [2] due to the size, efficiency and extent of solar cells and wind turbines [24]. The above-mentioned methods are examples of energy harvesting in large scale, but there are also ways in which energy harvesting can be applied in a much smaller scale that can provide power in the range of a few milliwatts [2], making it possible to use it as an alternative source of power for microelectronics. Sources of energy that can provide these small, but sufficient amounts of energy can be from the movement of a person, heat extracted from the body[2], the stray electric field or the stray magnetic fields surrounding an AC power cable [24][16].

When harvesting energy in such a small scale, it is usually the case that the energy is not sufficient enough to constantly provide power to the system. In these situations, an energy management circuit, as illustrated in fig. 2.1, is needed in order to accumulate enough energy from the energy harvesting source up until the point that it can provide sufficient power for the system to function properly. These energy management circuits consist of a rectifier circuit and a capacitor for storage of the energy, combined with a latch circuit which discharges the storage capacitor when the energy stored reaches a certain voltage.

![Block diagram of a typical energy harvesting circuit](image)

**Figure 2.1:** Block diagram of a typical energy harvesting circuit
2.3 The electromagnetic field

An electric charge has an electric field, $E$, which defines the standard force (the radius vector of the electric intensity of the charge measured in volts per meter) [26]. This means that the conductors in a cable will contain electric charges with electric fields as long as it is plugged into an active outlet, even if there is no current flowing in the cable. Fig. 2.2 shows an illustration of the electric field of a point charge.

![Figure 2.2: Illustration of the electric field of a point charge [8]](image)

In addition to the electric field caused by static charges, there also exists a magnetic field which is generated by the charges in motion [18]. If there is current flowing through the conductors in a cable, the electric charges of the conductors will be set in motion and a magnetic field will be generated around the conductor in a circular form [20] and its direction is dependent on how the current is flowing as illustrated in fig. 2.3.

![Figure 2.3: Illustration of the magnetic field of a moving charge [6]](image)
2.4 Capacitor

A capacitor is an electrical component used to store energy in an electric field. The energy stored in a charged capacitor is

\[
J = \int IVdt = \int \frac{dQ'}{dt} \frac{Q'}{C} dt = \frac{1}{C} \int_0^Q Q'dQ' = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} C V^2
\]

(2.1)

where \(C\) is the size of the capacitor in Farad, \(V\) is the voltage in Volt and \(J\) is the energy in Joule[3].

This information is useful when determining the size of a storage capacitor and the energy consumed by a circuit is known. The energy consumption in Watts can be calculated by

\[
P = U \cdot I.
\]

(2.2)

The energy in Joule can be calculated by

\[
J = P \cdot t.
\]

(2.3)

The electric charge, measured in Coulomb, can be calculated in the following way

\[
Q = I \cdot t.
\]

(2.4)

The energy, measured in Joule, can be calculated in the following way

\[
J = V \cdot Q.
\]

(2.5)

Hence the expression to calculate the storage capacitor \(C\) is

\[
C = \frac{2 \cdot J}{V^2}.
\]

(2.6)

where \(P\) = power (Watt), \(J\) = energy (Joule), \(V\) = electric potential (Volt), \(I\) = current (Ampere), \(Q\) = electric charge (Coulomb), \(C\) = capacitance (Farad), \(V\) = potential difference (Voltage) and \(t\) = time (seconds).

2.4.1 Expression for storage capacitor

To calculate the required capacitance of the storage capacitor one needs to know the amount of energy that the circuit needs to perform one transmission. To estimate this, one needs to know the maximum voltage the capacitor will be charged to, the minimum input voltage of the voltage regulator, the output voltage of the voltage regulator, the current consumption of the circuit and the time required to perform one transmission.
When estimating the total energy required for one transmission one has to consider three main aspects, the power consumption of the circuit, the power loss in the voltage regulator and the energy required to charge the capacitor to the minimum operating voltage of the voltage regulator.

The power consumption of the circuit can be found using equation 2.2. To find the power loss of the voltage regulator, one can use that

\[ P_{\text{loss}} = P_{\text{in}} - P_{\text{out}} \]  

(2.7)

to find \( P_{\text{loss max}} \) and \( P_{\text{loss min}} \) and then calculate \( P_{\text{loss mean}} \) by using that

\[ P_{\text{loss mean}} = \frac{P_{\text{loss max}} + P_{\text{loss min}}}{2} \]  

(2.8)

The stored energy required to reach the minimum operating voltage of the voltage regulator can be expressed using equation 2.1.

Combining these expressions, one can describe the total energy needed for one transmission, \( E_{\text{needed}} \) as

\[ E_{\text{needed}} = \left( \frac{U_{\text{in max}} - U_{\text{out}}}{2} + \frac{U_{\text{in min}} - U_{\text{out}}}{2} \right) \cdot I \cdot T + C \cdot \frac{U_{\text{in min}}^2}{2}. \]  

(2.9)

Equation 2.9 can be simplified to

\[ E_{\text{needed}} = \left( \frac{U_{\text{in max}} + U_{\text{in min}}}{2} \right) \cdot I \cdot T + C \cdot \frac{U_{\text{in min}}^2}{2}. \]  

(2.10)

The energy stored in a capacitor with capacitance \( C \) at the voltage \( U_{\text{in max}} \) can be expressed as

\[ E_{\text{stored}} = \frac{C \cdot U_{\text{in max}}^2}{2} \]  

(2.11)

using equation 2.1.

To find the smallest possible capacitance \( C \), \( E_{\text{needed}} \) and \( E_{\text{stored}} \) should be equal, hence

\[ E_{\text{stored}} - E_{\text{needed}} = 0 \]

\[ \left( \frac{U_{\text{in max}} + U_{\text{in min}}}{2} \right) \cdot I \cdot T + C \cdot \frac{U_{\text{in min}}^2}{2} - C \cdot \frac{U_{\text{in max}}^2}{2} = 0 \]  

(2.12)

\[ \left( \frac{U_{\text{in max}} + U_{\text{in min}}}{U_{\text{in max}}^2 - U_{\text{in min}}^2} \right) \cdot I \cdot T = C. \]
2.5 Operational amplifier

An operational amplifier, with its symbol shown in fig. 2.4, is a device that amplifies the voltage difference of the inputs[17].

![Symbol of the operational amplifier](image)

*Figure 2.4: Symbol of the operational amplifier*

An ideal operational amplifier has an infinitely high gain, infinitely high input resistance, and infinitely low output resistance. Even though there are no ideal operational amplifiers, real-world operational amplifiers still possess the ability to provide a high gain and even if the input voltages might only differ a bit, the large amount of gain in the operational amplifier will cause the output to saturate. The saturation levels are defined as the supply voltages of the operational amplifier, and can be studied in fig. 2.5[17].
Figure 2.5: Characteristics of an operational amplifier without feedback

In order to prevent this, the output of the operational amplifier can be fed back into one of the inputs and an application circuit can be designed in order to get a wanted behavior of the output signal. Fig. 2.6 shows an inverting operational amplifier[17] where the output is fed back into the negative input.

Figure 2.6: Circuit diagram of an operational amplifier with negative gain
Since the negative input has a high resistance, this point can be seen as a virtual
ground meaning the voltage at this point is approximately zero without any con-
nection to an analog ground. This causes the current to flow through R1 and R2,
which implies that the input voltage lands over R1 and the output voltage over
R2, giving[17]

\[
\frac{U_{in} - 0}{R1} = \frac{0 - U_{ut}}{R2}
\]  

(2.13)

This gives an equation for the gain that can be written as

\[
A = \frac{U_{ut}}{U_{in}} = -\frac{R2}{R1}.
\]  

(2.14)

### 2.5.1 High-pass filter

Fig. 2.7 shows an inverting high-pass filter with a cut-off frequency calculated
with

\[
f = \frac{1}{2 \cdot \pi \cdot R1 \cdot C}.
\]  

(2.15)

![Image of a high-pass filter circuit](image)

**Figure 2.7: First order high pass filter with negative gain**

At frequencies lower than the cut-off frequency, the capacitor C has a high impedance
\((Z_c >> R1)\) causing the impedance of \(Z_c + R1\) to be \(Z_c\). This implies that the gain
is increasing up until the cut-off frequency as seen in fig. 2.8

At frequencies higher than the cut-off frequency, the capacitor C have a low
impedance \((Z_c << R1)\) causing the impedance of \(Z_c + R1\) to be \(R1\). This implies
that the gain of the circuit from the cut-off frequency and beyond is calculated
with equation 2.14 and its behaviour can be seen in fig. 2.8.
Figure 2.8: Characteristics of a first order high pass filter with negative gain
2.5.2 Low-pass filter

Fig. 2.9 shows an inverting low-pass filter with a cut-off frequency calculated with

$$f = \frac{1}{2 \cdot \pi \cdot R_2 \cdot C}$$

(2.16)

![Low-pass filter diagram](image)

*Figure 2.9: First order low-pass filter with negative gain*

At frequencies higher than the cut-off frequency, the capacitor C have a low impedance ($Z_c \ll R_2$) causing the parallel connection of C and $R_2$ ($C||R_2$) to be small at high frequencies. This implies that the gain drops linearly after the cut-off frequency as seen in fig. 2.10.

At frequencies lower than the cut-off frequency, the capacitor C have a high impedance ($Z_c \gg R_2$) causing the parallel connection of C and $R_2$ ($C||R_2$) to be $R_2$. This implies that the gain of this circuit can be calculated with equation 2.14 up until the cut-off frequency as seen in fig. 2.10.
2.6 Multicore cables

A multicore power cable carrying alternating current used for powering consumer electronics usually consists of either two conductors called the phase and the neutral or three conductors which in addition to the other two also has a protective earth as illustrated in fig. 2.11.

As described in section 2.3, a conductor carrying alternating current will have a surrounding magnetic field. In a multicore cable, both the phase and the neutral wire will generate magnetic fields but with opposite directions. Clamping a toroidal core around the multicore cable will result in zero induced energy since the two opposite magnetic fields will cancel out.
2.7 Linear hall effect sensor

The linear hall effect sensor is a component that is sensible to changes in the magnetic field. The linear hall effect sensor is a small component with three pins, a VCC pin, a GND pin and an output voltage pin. When a magnetic field is applied in the presence of the linear hall effect sensor, the output voltage pin provides a voltage that is proportional to the magnetic field.[1]

2.8 Analog to digital conversion

An analog to digital converter is a device with an analog signal as its input from which it samples values with some frequency, converting them into digital values [19]. There is no value at the time in between samples which implies that the higher the sample frequency of the ADC, the better the reconstruction of the analog signal will be in the digital domain.

![Figure 2.12: Illustration of the sampling process of an analog signal [7]](image)

Since the analog value is converted into a digital value, the digital value will be rounded up or down to the nearest value, determined by the resolution of the ADC. This is called quantization, and the higher the resolution of the ADC, the better the analog value is represented in the digital domain.

2.9 Serial Peripheral Interface

Serial Peripheral Interface, SPI, allows synchronous data transfer between microcontrollers and peripheral devices such as wireless data transceivers. Every transmission of data is always between a master which is the active device that initiates the transmission and generates the clock signal, and a slave which is the passive device. The slave can not generate a clock signal by its own and only gets
active when the master initiates a transfer. One data bit is shifted from the master to the slave and from the slave to the master each clock cycle, meaning that after eight clock cycles, one byte of data has been transferred from the master to the slave and vice versa [9].

2.10 ShockBurst™ mode

The nRF905 transceiver has an on-chip feature called ShockBurst™ which handles some data processing so that the microcontroller used together the nRF905 transceiver does not have to perform these operations[22]. The nRF905 has two ShockBurst™ modes, ShockBurst™ RX (receive mode) and ShockBurst™ TX (transmit mode), each containing a different set of features, which can be selected by writing different ports of the nRF905 high or/and low.

2.10.1 ShockBurst™ TX

In ShockBurst™ TX, a preamble and CRC are automatically generated when a data transmission is started. Once the transmission is complete, the Data Ready (DR) pin is set high. A data packet in ShockBurst™ TX mode, as illustrated in fig. 2.13, contains a 10-bit preamble, between one to four address bytes, one to 32 payload bytes, and zero to two CRC bytes.

| Pre-amble | ADDR | PAYLOAD | CRC |

*Figure 2.13: Illustration of an assembled data packet in ShockBurst™ TX mode*

2.10.2 ShockBurst™ RX

In ShockBurst™ RX, the Carrier Detect (CD) pin is set high if the nRF905 senses a carrier at the selected frequency, the Address Match (AM) pin is set high if the address of the nRF905 agrees with the received address and the Data Ready (DR) pin is set high when a valid data packet has been received.
3 Method

3.1 Getting an overview of the system

As described in the thesis scope, the goal with this project is to design a wireless, non-invasive, current sensing node which should be able to run without a battery as its power supply. Designing a system can seem complex at the first glance, and therefore it is useful to break down the system into smaller subsystems in order to get a better overview of what needs to be done. To create a system which should run on harvested energy, the first thing that needs to be investigated is what sources of energy are present in the environment that the system should function in. Knowing the sensor node should be attached to the power cable, this thesis focuses on the method of energy harvesting from the electric field of a multicore power cable connected to a 230 V AC outlet.

The system should also include some form of device that, in a non-invasive way, can sense if current is flowing in a power cable. The meaning of non-invasive might be fairly relative, and in this thesis, non-invasive current sensing is defined as not having to connect anything between the power cable and the 230 V AC outlet. Knowing that there is alternating current flowing through the cables that the sensor node should monitor, the work in this thesis makes use of the fact that alternating current generates a magnetic field which can be detected.

The output result of the non-invasive current sensor, running on harvested energy, should be wirelessly transmitted from the sensor node to a receiver where the status code is displayed.

A sketch of the system is shown in fig. 3.1 and the behavior is illustrated in fig. 3.2.
The indicator can be placed anywhere inside the home, preferably where it reminds the person leaving home that no devices are left turned on. Knowing the fundamental requirements of the system, one can start looking into whether there are any constraints on size, weight, timing, power consumption and accuracy. Given the fact that the sensor is monitoring the flow of current of devices that may overheat or in other ways cause a fire hazard, the need of an accurate result is of the essence. The output should be produced within a certain amount of time since the status of the device can change quickly from on to off, and the
person might be leaving their home right after that event.

## 3.2 Energy harvesting circuit

The purpose of the energy harvesting circuit is to store the harvested energy in a capacitor up to a certain voltage, at which it discharges in order to provide the rest of the circuit with enough energy so that it can perform its intended operations.

![Circuit Diagram](image)

**Figure 3.3: Circuit diagram of the energy harvesting circuit**

Fig. 3.3 show the schematic of the energy harvesting circuit. To the left in the circuit the diodes D1 and D2 are placed to rectify the current from the energy harvesting source, making it possible to store the energy in the storage capacitor C1 (further explained in section 3.4.2). The energy harvesting circuit is connected to the energy harvesting source, which, in this case, is a shield of a conducting material surrounding a 230 V AC power cable as shown in fig. 3.4 and 3.5. In this project, aluminum foil and copper tape are used.
To the right of the storage capacitor C1, there is a latch circuit made of an NPN-transistor, a PNP-transistor, a Zener diode and a resistor. The Zener diode initially prevents current from flowing into the base of Q2, making the path from the collector to emitter of Q2 non-conducting. Having connected the base of Q1 to the collector of Q2, the path between the collector and the emitter of Q1 is also non-conducting. This means that as long as the voltage over the storage capacitor C1 is less than the breakdown voltage of the Zener diode D1, no current should flow through this section of the circuit.

When the voltage over C1 exceeds the breakdown voltage of the Zener diode D1, a current will flow into the base of Q2, which will trigger the gate of the latch circuit formed by the two transistors Q2 and Q1. This will cause Q2 to conduct, allowing current to flow from the storage capacitor C1 to the voltage regulator. Once the latch circuit starts conducting no more gate voltage is required to keep...
the circuit in a conducting state. The load is now powered by the energy discharged from the storage capacitor C1 and will start to perform its operations. Once the load is done, a signal connected to the base of Q3 is set to high causing Q3 to conduct and enough current to flow through R2 to disconnect the latch which will put the circuit back into charging state.

3.2.1 Simulation of the harvesting circuit

Before ordering components, some simulations in Multisim were done in order to verify the functionality of the energy harvesting circuit. Fig. 3.6 shows the circuit drawn in Multisim. To simulate the harvesting shield, an AC power source is introduced which is connected to the circuit through a 100 pF capacitor.

![Energy harvesting circuit simulated in Multisim](image)

**Figure 3.6: Energy harvesting circuit simulated in Multisim**

Fig 3.7 shows the voltage over the storage capacitor when running a transient analysis.

![Transient Analysis](image)

**Figure 3.7: Simulation result of the energy harvesting circuit in Multisim**

From the simulation result, one can see that the circuit works as expected. The
voltage over the capacitor rises until it exceeds the breakdown voltage of the Zener diode which causes a discharge of the storage capacitor through the latch circuit. When the capacitor is fully discharged, no current will flow through the latch circuit which will cause it to stop conducting and the circuit will go back to accumulate charge.

### 3.2.2 Voltage regulators

The voltage over storage capacitor C1 in fig 3.3 will increase together with the energy stored. When the circuit is in the discharge state, the voltage over C1 might be higher than the supply voltage of the load. To solve this problem, a voltage regulator is introduced.

A linear voltage regulator can in a simple way bring down a higher voltage to a lower level which is either an adjustable or a fixed output voltage. To use this device in a circuit, one simply connects the input pin of the linear voltage regulator to the source, the ground pin to ground and the output pin to the rest of the circuit to provide a steady and regulated voltage as illustrated in fig. 3.8.

![Figure 3.8: Symbol for the linear voltage regulator](image)

When choosing the voltage regulator, key features such as low dropout voltage (the voltage in addition to the controlled output voltage that the regulator must have as input in order to keep the output voltage at a steady level) and low quiescent current (the current consumed by the regulator when operating) was studied in order to pick a voltage regulator that can perform these kind of operations with a low power consumption.
3.3 Wireless data transmission node

As described in section 3.1, the result from the current sensing node should be sent wirelessly to a receiver which will display the status of the device.

3.3.1 Components

Since the aim is to be able to run the device only on harvested energy without having a power supply in the form of a battery, the constraints of the power consumption are of the essence. In order to keep the power consumption to a minimum, a lot of focus will be put into finding the right components to use, making the wireless transmission of data as low power consuming as possible. In order to design a circuit suitable for harvesting enough energy, one need information regarding the power consumption of the components needed to wirelessly transmit the data.

3.3.1.1 RF transceiver

Since the application is running on a very limited power supply, the time needed for the device to power up, initialize and transmit data needs to be fast as well as the energy consumed for one transmission have to be as low as possible.

Seen in table 3.1 are the different RF transceivers that were evaluated and compared to each other.

<table>
<thead>
<tr>
<th>Device</th>
<th>Supply voltage</th>
<th>Transmit current</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBee®</td>
<td>2.8 – 3.4 V</td>
<td>45 mA (@ 3.3 V)</td>
</tr>
<tr>
<td>nRF905</td>
<td>1.9 - 3.6 V</td>
<td>9 - 30 mA</td>
</tr>
<tr>
<td>HumPRO</td>
<td>2.0 - 3-6 V</td>
<td>22 - 40.5 mA</td>
</tr>
</tbody>
</table>

*Table 3.1: Comparison of suitable RF transceiver devices [14] [22] [25]*

Because of the availability to configure its settings, the nRF905 was selected over the other two. Looking at the datasheet [22], in addition to its low supply voltage of 1.8-3.8 V, parameters such as the output power in dBm, size of transmit payload and transmit address can be adjusted to transmit only the absolute necessary. The 9 mA transmit-current of the nRF905 is also lower than the other choices which are a huge benefit.

3.3.1.2 Microcontroller

A microcontroller is needed to compute the sensor data and transmit the resulting data wirelessly through the RF-transceiver. An important property of the microcontroller is the power consumption, but even more important is that it supports all the features required for the application. For this application, the microcontroller need to support SPI (explained further in section 2.9) which is required in order to communicate with the RF-transceiver. In addition to the three pins needed for SPI (MISO, MOSI, and SCK), the microcontroller need to
have a number of available I/O pins to select the different modes of the nRF905. Another important feature is the presence of ADC ports (explained further in section 2.8) which are necessary for the current-sensing part. The search for a microcontroller was narrowed down to Atmel’s tinyAVR family.

Seen in table 3.2 are the different microcontrollers that were evaluated and compared to each other.

<table>
<thead>
<tr>
<th>Device</th>
<th>Supply voltage</th>
<th>Current consumption</th>
<th>Pins</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATmega8L</td>
<td>2.7 V - 5.5 V</td>
<td>3.6 mA @ 4 MHz, 3 V</td>
<td>28</td>
</tr>
<tr>
<td>ATtiny13A</td>
<td>1.8 V - 5.5 V</td>
<td>190 µA @ 1 MHz, 1.8 V</td>
<td>8</td>
</tr>
<tr>
<td>ATTiny861V</td>
<td>1.8 V - 5.5 V</td>
<td>300 µA @ 1 MHz, 1.8 V</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 3.2: Comparison of suitable microcontrollers**

From the tinyAVR family, ATtiny861V was chosen due to the fact that it supports both SPI and ADC. The power consumption of the ATtiny861V is low, only 300 µA with a system clock at 1 MHz and supply voltage at 1.8 V [10].

### 3.3.2 Using the microcontroller with the RF-transceiver

The connections between the microcontroller and RF-transceiver can be seen in fig. 3.9.

![Figure 3.9: Circuit diagram of the transmitter circuit](image)

The ATtiny861 uses the SPI protocol to communicate with the nRF905. The nRF905 has a number of settings that have to be specified each time the module is restarted. The settings are modified by setting or clearing bits in the CR
(Control Register) of the nRF905. In this application, low power consumption is of the essence, hence the nRF905 is set up for maximum speed and minimal power consumption, which can be seen in table 3.3. A brief description of the most critical settings follows. A more in-depth description is to be found in the data sheet[22].

Output power is set to -10 dBm, which is the lowest setting and consumes the least power. The RX and TX address width is set to two bytes. The lowest setting is one byte but when set to one byte the modules failed to communicate successfully. The RX and TX payload is set to one byte since the applications are only transferring small amounts of data. CRC (Cyclic Redundancy Check) is set to 16 bits. This setting was disabled in an attempt to lower the length of the transmitted data package, but when disabled, the transmission failed.

<table>
<thead>
<tr>
<th>Output power</th>
<th>-10 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX address</td>
<td>2 Bytes</td>
</tr>
<tr>
<td>TX payload</td>
<td>1 Byte</td>
</tr>
<tr>
<td>Crystal frequency (MHz)</td>
<td>16</td>
</tr>
<tr>
<td>Output clock frequency (MHz)</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Table 3.3: Settings of the nRF905

The nRF905 has five different operating modes as can be seen in fig. 3.10, each used for different situations.

<table>
<thead>
<tr>
<th>PWR_UP</th>
<th>TRX_CE</th>
<th>TX_EN</th>
<th>Operating Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X</td>
<td>X</td>
<td>Power down and SPI programming</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>X</td>
<td>Standby and SPI programming</td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>0</td>
<td>Read data from RX register</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Radio Enabled - ShockBurst™ RX</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Radio Enabled - ShockBurst™ TX</td>
</tr>
</tbody>
</table>

Figure 3.10: nRF905 operating modes

The code for the ATtiny861 in the transmitter circuit can be found in Appendix A. A brief description of the code follows below.

First, the microcontroller is initialized, I/O ports and SPI registers are set up. The CE, PWR, and TX_EN pins are cleared to ensure that the nRF905 is in power-down mode. After the initialization of the microcontroller, the CSN pin is cleared to initiate an SPI communication with the nRF905. All the settings bytes are now shifted into the control register of the nRF905 and the CSN pin is set high to end the SPI communication. The PWR pin is now set high to put the nRF905 in standby mode. Now the transmit address and payload are sent to the address and payload registers of the nRF905 over SPI. The nRF905 is now ready to transmit a data package and the transmission is initiated by pulsing the CE pin. The microcontroller is now done and idles until the power is cut.
The flowchart seen in 3.11 describes the life cycle of the system, starting from the moment it powers up until it has performed its intended operations and then shuts itself down.

**Figure 3.11: Flowchart for the RF transmitter**
3.3.3 Estimating the power consumption

To estimate the power consumption, the time for one wireless data transmission also has to be known. In order to measure the time taken for one wireless data transmission, one channel of a logic analyzer was connected to the DR pin on the nRF905. The ATtiny861 is now programmed to only perform one data transmission. To check if a transmission is completed, one can either use the DR pin of the nRF905 or the DR bit in the status register of the nRF905 [22]. Both the DR pin and the DR bit will be set high after a transmission, however, the DR pin is used in this configuration because it is unnecessary to implement the functionality of the DR pin in software when it is already implemented in hardware. Another channel of the logic analyzer was connected to VCC and the logic analyzer was set to trigger on this channel. The result of the test is presented in fig. 4.15 in section 4.5.1.

The time that the nRF905 is in standby mode and transmission mode (explained in fig. 3.10) is shown in fig. 4.16 and fig. 4.17. The high flank of the CE pin indicates the mode switch from standby mode to transmission mode. When the DR pin is set high the transmission is completed and the transceiver is once again put in standby mode. As seen in fig. 4.16, the time that the nRF905 is in standby mode is about 5.96 ms, followed by about 1.65 ms in transmission mode as seen in fig. 4.17. In other words, the system is in transmission mode for 21.7% of the total transmission time and in standby mode for 78.3%.

According to table 9 in the datasheet for nRF905 [22], the current consumption in transmission mode when the nRF905 has been configured according to table 3.3 are about 9 mA and 32 μA when in standby mode. According to fig. 20-1 in the datasheet for ATtiny861 [10], the current consumption when running on 3.3 V supply voltage at 1 MHz is about 0.58 mA.

Knowing this, one can now calculate a theoretical value of the total power consumption as

\[
(0.217 \cdot 9mA) + (0.782 \cdot 32\mu A) + 0.58mA = 2.56mA.
\]  
(3.1)

The theoretical energy consumption in Watts can now be calculated using

\[
2.56mA \cdot 3.3V = 8.45mW
\]  
(3.2)

and the energy required for one wireless data transmission according to equation 2.3 is

\[
8.45mW \cdot 7.61ms = 64.29\mu J.
\]  
(3.3)

The energy required from equation 2.3 can be used to calculate a theoretical value of a storage capacitor.
3.3.4 Measuring the power consumption

3.3.4.1 Average

In order to verify the specified current consumption of the different modes of the nRF905, tests were done by connecting a multimeter in series with the nRF905 as seen in fig. 3.12.

![Circuit for measuring the current consumption of the nRF905](image)

**Figure 3.12: Circuit for measuring the current consumption of the nRF905**

To measure the current consumption in transmit mode, the ATtiny861 runs a program that locks the nRF905 in transmit mode. The specified current consumption in this mode is 9 mA. When the circuit is powered with 3.3 V, the multimeter shows a current of 9.03 mA.

To measure the current consumption in standby mode, the ATtiny861 was programmed to lock the nRF905 in standby mode. The specified current consumption in this mode is 32 µA. When the circuit is powered with 3.3 V the multimeter shows a current of 26 µA.

To measure the combined current consumption of the nRF905 and the ATtiny, the multimeter was connected as shown in fig. 3.13. The current consumption in transmit mode is now measured to 10.04 mA and 1.02 mA in standby mode.
The power consumption can now be calculated in a similar way as in section 3.3.3 as
\[
(0.217 \cdot 10.04m\text{A}) + (0.782 \cdot 1.02m\text{A}) = 2.98m\text{A}.
\] (3.4)

The theoretical energy consumption in Watts can now be calculated as
\[
2.98m\text{A} \cdot 3.3V = 9.83m\text{W}
\] (3.5)

by using equation 2.2, and the energy required for one wireless data transmission according to equation 2.3 as
\[
9.83m\text{W} \cdot 7.61m\text{s} = 74.8\mu\text{J}.
\] (3.6)

### 3.3.4.2 Dynamic

Another more accurate method for measuring the current consumption is to use an oscilloscope to measure the voltage drop over a resistor[21]. To perform the test, the circuit was connected to the oscilloscope as shown in fig. 30 in RF Performance Test Guidelines [21].

The resistor Rm is 10 Ohms. Rm should be 1-10 Ohms where a larger resistor will increase the voltage drop but also the VDD ripple in the RF device [21]. The result of this test is presented in section 4.4.
3.4 Wireless data transmission node with the energy harvesting circuit

Fig. 3.14 shows the wireless data transmission node connected together with the energy harvesting circuit.

![Circuit diagram](image)

**Figure 3.14: Circuit diagram of the wireless data transmission node together with the energy harvesting circuit**

The storage capacitor is charged to a certain voltage in order to accumulate sufficient energy to provide to the rest of the circuit. When a wireless data transmission is complete, the Data Ready pin, DR, is set high which will make Q3 to conduct and allow current to flow down through R2, which will cause the latch circuit to stop conducting and put the energy harvesting circuit back into charging state.

### 3.4.1 Energy consumption of the wireless data transmission node with the voltage regulator

In addition to the power consumption of the ATtiny861 and the nRF905, the voltage regulator also dissipates power, and for our particular application, we need to choose a voltage regulator that is as power-efficient as possible.

The NTE1904 linear voltage regulator was evaluated for its usage in the application circuit. It has a fixed output voltage of 3.3 V, a maximum output current of 1 A, a dropout voltage of 0.45 V and a quiescent current of 0.5 mA typical [12].

The NTE1904 was chosen as the voltage regulator to provide the ATtiny861 and the nRF905 with a 3.3 V supply voltage. The quiescent current of 0.5 mA was verified by connecting an ampere-meter in series with the circuit as can be seen in fig. 3.15. According to the readings of the multimeter, the quiescent current
is 0.52 mA. The combined current consumption for the ATtiny861, the nRF905, and the voltage regulator can now be calculated to $2.98\,mA + 0.52\,mA = 3.5\,mA$.

3.4.1.1 Calculating power loss from regulator

To calculate the power loss, 

$$P_{\text{loss}} = P_{\text{in}} - P_{\text{out}} = (V_{\text{in}} - V_{\text{out}}) \cdot I_{\text{out}}$$

(3.7)

can be used[17].

In this application, $V_{\text{inmax}}$ is dependent on the Zener diode D1. With a Zener diode with a Zener voltage 6.8 V, $V_{\text{inmax}}$ is measured to $V_{\text{inmax}} = 7.7\,V$

$V_{\text{out}}$ is fixed at 3.3 V.

$V_{\text{inmin}}$ is dependent on the dropout voltage of the voltage regulator. For NTE1904 $V_d = 0.2\,V$ [22] hence $V_{\text{inmin}} = V_{\text{out}} + V_d = 3.3\,V + 0.3\,V = 3.5\,V$.

$I_{\text{out}}$ is calculated to 3.5 mA.

With these values $P_{\text{lossmax}}$ can be calculated to

$$P_{\text{lossmax}} = (V_{\text{inmax}} - V_{\text{out}}) \cdot I_{\text{out}} = (7.7\,V - 3.3\,V) \cdot 3.5\,mA = 15.4\,mW.$$ 

And $P_{\text{lossmin}}$ can be calculated to

$$P_{\text{lossmin}} = (V_{\text{inmin}} - V_{\text{out}}) \cdot I_{\text{out}} = (3.5\,V - 3.3\,V) \cdot 3.5\,mA = 0.7\,mW.$$ 

$P_{\text{lossmean}}$ can now be calculated by

$$P_{\text{lossmean}} = (P_{\text{lossmax}} + P_{\text{lossmin}})/2 = (15.4 + 0.7)/2 = 8.05\,mW.$$ 

**Figure 3.15:** Circuit for measuring the current consumption of the NTE1904 voltage regulator
3.4.2 Storage capacitor

Since the aim is to run the application without a battery and only on harvested energy, a capacitor is used in order to store the harvested energy. The capacitance (Farads), as well as the voltage the storage capacitor is charged to, are the two key parameters in which the amount of energy stored are determined.

One might think that picking the largest capacitor available is a safe bet, but the physical properties of a capacitor implies that the larger the capacitance, the longer the charging time. This means that the storage capacitor has to be picked carefully, in order to keep the charging time to a minimum, but at the same time store enough energy so that the circuit can function correctly.

To find the minimal capacitance of the storage capacitor, equation 2.12 can be used with some measured values.

\[
U_{inmax} = 7.7 \text{ V} \\
U_{inmin} = 3.5 \text{ V} \\
U_{out} = 3.3 \text{ V} \\
T = 7.61 \text{ ms} \\
I = 3.5 \text{ mA}
\]

\[C \text{ can be calculated to } 6.34 \mu F \text{ as}
\]

\[
\left(\frac{7.7V + 3.5V}{7.7V^2 - 3.5V^2}\right) \cdot 3.5mA \cdot 7.61ms = 6.34\mu F.
\]

(3.8)

The calculated value of the storage capacitor are now known and a capacitor with a value close to the calculated value can be chosen.
3.5 Current sensing

As described in the thesis scope, one of the main tasks brought up in this thesis is to, in a non-invasive way, sense if there is current flowing through a multicore 230 V AC power cable. Sensing the current in a non-invasive way, means in this case that nothing should be connected between the 230 V AC power cable and the power outlet, but instead the current sensing device should be placed around the power cable. As explained in section 2.3, the magnetic field generated by the alternating current in the power cable can be detected by placing linear hall effect sensors (explained in section 2.7) around the multicore cable, taking advantage of the layout of the conductors (explained in section 2.6). Since this solution is dependent on placing the hall effect sensors close to the conductors in the power cable, rotating the power cable can affect the output of the sensors. Best case scenario is when each sensor is as close to a conductor as possible, and worst case scenario is when each sensor is as maximum distance from the conductors.

3.5.1 The current sensing circuit

A current sensor circuit designed by Modern Device [11] was found and used as inspiration. In this section, the circuit will be tested, evaluated and modified for use in this application.

![Circuit Diagram](image)

Figure 3.16: Circuit diagram of the full current sensor circuit

The fact that the conductors are separated, if only by a bit, can be used for the purpose of sensing if there is current flowing in the power cable. The non-invasive current sensing device is making use of this fact and is built on the principle that when placing two linear hall effect sensors near the multicore cable with a small distance separated from each other, the linear hall effect sensors will be closer to one of the conductors each. Since the current flowing in the power cable is 50 Hz in Sweden, some necessary filtering is introduced to make sure that the output only consists of the frequencies of interest. By rewriting equation 2.16 and picking an arbitrary resistor R,

\[ c = \frac{1}{2 \cdot \pi \cdot R \cdot f} \]  (3.9)
can be used to calculate the capacitor C.

Selecting a 4.7 kΩ resistor for the lower cut-off frequency of about 34 Hz gives a capacitor value of

\[ \frac{1}{2 \cdot \pi \cdot 4700 \Omega \cdot 34 \text{Hz}} = 1 \mu F. \] \(\text{(3.10)}\)

Selecting a 220 kΩ resistor for the higher cut-off frequency of about 362 Hz gives a capacitor value of

\[ \frac{1}{2 \cdot \pi \cdot 220000 \Omega \cdot 362 \text{Hz}} = 2 nF. \] \(\text{(3.11)}\)

The filtered signals are then fed into an operational amplifier. Since one hall effect sensor is closer to the hot wire and the other one closer to the neutral wire, the output voltages of the hall effect sensors will have the same amplitude but with the difference that one voltage will be negative and one will be positive. Having these two opposite voltage values as the input of the operational amplifier, the output of the operational amplifier will have an even more significant value as a result of the properties of an operational amplifier as described in section 2.5.

The output before C4 can be seen in fig. 4.8. When there is current flowing in the power cable, the output of the operational amplifier is a sine wave with an offset caused by the hall effect sensors. When there is no current flowing in the power cable, the output is only the offset voltage of the hall effect sensors with some ripple.

To eliminate this offset, a capacitor is placed in series with the output, allowing only AC voltage to pass. The output after C4 is centered around zero voltage and can be studied in fig. 4.9 where a 100 nF foil capacitor are used.

In order to get a steady output signal, a rectifier circuit followed by a peak detector circuit is introduced. Since the output at this stage is centered by zero voltage, the diode will block the negative part of the sine wave, allowing only the positive half-period of the output to flow through as can be seen in fig. 4.11. This rectified output are then smoothed out by a filter capacitor which produces the final output signal of the current sensor as can be seen in fig. 4.12.
3.5.2 Optimizing the circuit

Fig. 4.12 shows the output of the whole circuit. A critical property of the circuit is the settling time of the output, meaning the time it takes for the output to produce a result which can be used in order to tell whether the output of the sensor is either positive or negative when it comes to determining if current is flowing in the cable. One can see that the settling time when there is no current flowing is about 800 ms. Compared to the time required to transmit a data package, 7.61 ms, 800 ms is a very long time. In an attempt to reduce the settling time, the capacitor C4 was changed to a 10 nF, the result is presented in fig. 4.13. One can see that the whole curve is lowered, and therefore also the settling time. However, it is still too long. Instead of looking at the signal when it is completely settled, one can check how long time it takes for the signal to settle enough so it is possible to distinguish the current off signal from the current on signal. Fig. 4.14 is a zoomed in version of the beginning of the output signals. After around 80 ms the signals differ enough to make a safe reading. 80 ms is still a lot compared to 7.61 ms so the pursuit for milliseconds continues. The next step taken was to remove the rectifier and measure directly after the capacitor C4 as shown in fig. 3.17. The result for C4=10 nF can be found in fig. 4.10 and for C4=100 nF in fig. 4.9. One can see that even with the small capacitor it takes some time to get rid of the DC offset. The final approach was to measure the signal at the output of the first operational amplifier, as shown in fig. 4.8. The settling time of the no current signal is now around 20 ms and even before that there is a peak on the sine wave that can be used to distinguish the signals. Using this approach, the only circuitry used is shown in fig. 3.17

![Circuit diagram of the optimized current sensor circuit](image)

*Figure 3.17: Circuit diagram of the optimized current sensor circuit*
3.5.3 The current sensing algorithm

The output from the current sensor was connected to one of the ADC pins of the ATtiny861. Some different methods for determining if the input signal is a sine wave (current on) or a DC with some ripple (current off) was tested. Time and accuracy were two very important aspects when choosing the method.

The chosen method is described below. The microcontroller is put in a loop where it reads the ADC value of the current sensor and checks if the value is over 2 V. This is done to avoid sampling the rise time of the current off signal. If the ADC value is over 2 V, the loop breaks, and the microcontroller starts to sample values of the current sensor. The 2.45 V DC offset caused by the hall effect sensors is subtracted from each sample, and if the value of the sample now is negative the sample value is subtracted from zero (sample=0-sample) making it positive. The sample is then added to a summation variable and after about 20 ms, the sampling is done and the summation variable is divided by the number of samples which gives the mean value of the samples. If the programming switch connected to pin 9 of the microcontroller is set high, the microcontroller will save the mean value to the EEPROM memory to use as a future reference for the DC offset with ripple. If the programming switch is set low, the microcontroller will instead read the reference mean value from the EEPROM memory, multiply it with a constant of 1.3 to get a safety margin, and compare it to the mean value to determine if the sampled signal is a DC offset with ripple or not. Fig. 3.18 shows a flowchart over the process.
Figure 3.18: Flowchart of the current sensing algorithm
3.5.4 Placement of the sensors

Some tests were done in order to see how much the placement of the power cable between the sensors affected the output from the sensor circuit. For this test, an oscilloscope was connected directly to the output of the sensor circuit in fig. 3.17 and the cable was turned a few degrees back and forward between tests.

3.5.5 Energy consumed by the current sensor and the voltage regulator

A multimeter was connected in series with the current sensing circuit shown in fig. 3.17 to find the current consumption.

![Circuit for measuring the current consumption of the current sensor](image)

*Figure 3.19: Circuit for measuring the current consumption of the current sensor*

The measured current consumption is 26.6 mA. Hence the power consumption at 5 V is 133 mW.
3.6 Powering the transmitter and the current sensor with harvested energy

Fig 3.20 shows a picture of the sensor node prototype. In order to run both the transmitter and the current sensor on harvested energy, some modifications on the harvesting circuit are required. The current sensor needs at least 4.5 V to operate. To achieve this, a 5 V LDO regulator is added to the circuit. Fig 3.21 shows a circuit diagram of the circuit, with the 5 V LDO regulator and the current sensor added.

Figure 3.21: Circuit diagram of the final circuit
3.6.1 Time consumption

The time consumption was measured by adding a feature to the ATtiny861 in the transmission circuit. The first thing that happens when the microcontroller is powered is that PB5 (Pin 8) is set high, and right before the microcontroller is done, PB6 is pulled low again. The time consumption can now easily be measured by measuring the width of the pulse that will appear on PB6. In fig. 4.18 one can see the time consumption when the current is off and when the current is on.

Some more test were done to verify the consistency of the result, the test results are shown in table 4.5.

3.6.2 Storage capacitor

To calculate the required storage capacitor for the whole circuit, one can use equation 2.12 with the following values. $U_{inmax}$ is measured to 8.73 V when using a Zener diode with a breakdown voltage of 9.1 V. $U_{inmin}$ is the lowest operating voltage of the 5 V voltage regulator.

\[
U_{inmax} = 8.73 \text{ V} \\
U_{inmin} = 5.2 \text{ V} \\
U_{out} = 5 \text{ V} \\
T = 25 \text{ ms} \\
I = 26.6 \text{ mA}
\]

The capacitance of the storage capacitor are calculated to

\[
(\frac{8.73V + 5.2V}{8.73V^2 - 5.2V^2}) \cdot 26.6mA \cdot 25ms = 188\mu F.
\] (3.12)

In section 3.3.4, the energy required to perform one wireless data transmission is calculated to around 75 $\mu$J. The amount of energy left in the storage capacitor after the sensor readings are done at 5 V can be calculated using equation 2.1,

\[
E_{5v} = \frac{1}{2} \cdot 188\mu F \cdot 5v^2 = 2.350mJ.
\]

The same equation can be used to calculate the energy in the capacitor at 3.3 V,

\[
E_{3.3v} = \frac{1}{2} \cdot 188\mu F \cdot 3.3v^2 = 1.024mJ.
\]

The amount of energy available for the nRF905 is calculated to

\[
E_{5v} - E_{3.3v} = 2.350mJ - 1.024mJ = 1.326mJ.
\]

Since 1.326mJ >> 75$\mu$J, one does not have to take the energy consumed by the nRF905 into account when choosing the storage capacitor for the whole system. To have some margin, a 200 $\mu$F storage capacitor was chosen.
3.7 Evaluating the harvesting shield

In order to design a harvesting shield that is fit for this intended operation, one must first gain knowledge in how the different materials and lengths of the shield come into play when it comes to efficiency. Different lengths of aluminum foil, showed in fig. 3.5, and copper tape, showed in fig. 3.4, was used when designing the shield. The system was then connected to an oscilloscope as seen in fig. 3.22 which made it possible to study the charging time of a 10 µF storage capacitor.

![Circuit diagram of the energy harvesting circuit together with the wireless data transmission node connected to an oscilloscope](image)

Figure 3.22: Circuit diagram of the energy harvesting circuit together with the wireless data transmission node connected to an oscilloscope

As the circuit is in charging state, the voltage over the storage capacitor C1 is increasing fairly linearly until the point that the voltage reaches the breakdown voltage of the Zener diode D1. This behavior of the circuit creates a sawtooth-shaped waveform that can be studied on the oscilloscope. The cursor function on the oscilloscope was used which allowed us to simply calculate the charging time in voltage per second by placing the two cursors between two voltage values 3.04 V and 6.00 V (ΔV) on the waveform and measure the difference in time (Δt) as illustrated in fig. 3.23.
Using this method, the increase in voltage over the storage capacitor per second can be calculated as

\[ \frac{\Delta V}{\Delta t} \] (3.13)

The measured values of the different shielding materials and the variety of lengths of the shield is presented in section 4.1.
3.8 Receiver module

A receiver module was constructed in order to verify the function of the system. Fig 3.24 shows a picture of the module connected to the logging device. The receiver module consists of, one ATtiny861, one nRF905 and two LEDs, one green, and one red. The circuit diagram of the receiver module is shown in fig 3.25 below:

![Figure 3.24: Picture of the receiver module connected to the logging device](image)

![Figure 3.25: Circuit diagram for the receiver module](image)
The code for the microcontroller can be found in Appendix B. A description of
the function follows. First the ATtiny861 and the nRF905 are initiated. TRX_CE
is then set high to put the nRF905 in receive mode. The program is now set in
a loop until the DR pin is set high, indicating that a package has been received.
The payload register of the nRF905 is transferred to the ATtiny861 over SPI. If the
payload contains the status code for on, the green LED will be lit up, otherwise
the red LED will be lit up.
3.9 Long term testing of the whole system

The whole system with the energy harvester, RF transmitter and current sensor put together requires a storage capacitor around 200 µF which is charged to 8.73 V to function properly. The charging process takes some time, even with a 3 m long aluminum harvesting shield the charging time is around 90 seconds. In order to ensure proper functionality of the system, a logging device was constructed for some long term testing.

The logging device is based on an Arduino. The Arduino has a ready to go USB interface. This is the main reason why the Arduino was chosen for this task. In fig. 3.26 one can see how the receiver is connected to the Arduino. A brief description of the code running on the Arduino follows below.

First the Arduino runs an initiation function where the serial interface and interrupts are initiated. Then the program is put in a loop, waiting for an interrupt. When the DR pin of the receiver is set high an interrupt is triggered on the Arduino. In the interrupt the Arduino checks which of the receiver’s out pins that are set high and transfers the result to a log file on a PC using the serial interface.

Figure 3.26: Connections between the Arduino and the receiver.
3.10 Range of the RF-transmitter

A range test was performed to evaluate the range of the nRF905 in an indoor environment. The plan was to place the transmitter in one corner of the office and move the receiver farther and farther away until a transmission would fail. However even when using the lowest possible output power on the transmitter (-10 dBm) we ran out of office space before the transmission failed. At that point, the receiver was placed in the opposite corner of the office, forcing the signal to travel a distance of approximately 30 m passing through several walls and one floor.

3.11 Different types of cables

Mainly two different types of cable were tested, the three core cable and the two core cable, both shown in fig 3.27 For this test aluminum foil with a length of 100 cm was used as a harvesting shield. To eliminate any other factors, the harvesting circuit was disconnected for this test and an oscilloscope was connected directly to the storage capacitor. The setup for the test is shown in fig 3.28.
3.12 Software used

A list of software used in this project follows below.

- Multisim was used for all simulations.
- Eagle was used for drawing the circuit schematics.
- Atmel studio was used for writing and compiling the code.
- eXtreme Burner in combination with a USBASP was used for programming the microcontrollers.
- Saleae Logic was used for the logic analyzer.
- AUTODESK 123D Circuits was used to create fig 3.26

**Figure 3.28: Test circuit for different cables**
In this chapter the results form the tests described in chapter three is presented.

4.1 Charging times of the harvesting materials

The measurement setup is described in section 3.7. Different lengths as well as different materials of the harvesting shield was tested. The results of the tests are presented in graphs and tables below.

4.1.1 Aluminum foil

Three samples were taken for each of the tested lengths (100 cm, 80 cm, 60 cm and 40 cm). The result of the test is presented in table 4.1 below. For all tests, the difference in volts ($\Delta V$) is equal to 2.96 V and the cable used is a three core cable.
From the sample data in table 4.1 the mean value for each length is calculated and divided by the difference in voltage to acquire the charge rate in volts per second is

\[
CR = \frac{\Delta V}{\sum X / n}
\]  

(4.1)

where CR = charge rate, X = data sample, n = number of samples, \( \Delta V \) = difference in voltage.

For example, the calculation of the charge rate for the length 100 cm is

\[
\frac{2.96V}{9.45s+9.4s+9.5s} = 0.313 \text{V/s}.
\]  

(4.2)

The charge rates for all the tested lengths can be found in table 4.2.

<table>
<thead>
<tr>
<th>Length [cm]</th>
<th>volts per second [V/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.313</td>
</tr>
<tr>
<td>80</td>
<td>0.240</td>
</tr>
<tr>
<td>60</td>
<td>0.168</td>
</tr>
<tr>
<td>40</td>
<td>0.087</td>
</tr>
</tbody>
</table>

*Table 4.2: Different lengths chosen of the aluminum foil*

4.1.2 Copper tape

The copper tape was tested in the same way as the aluminum foil, three samples for each tested length were collected. The result is presented in table 4.3.
### 4.1 Charging times of the harvesting materials

<table>
<thead>
<tr>
<th>Length [cm]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
</tr>
<tr>
<td>80</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>10.5</td>
</tr>
<tr>
<td>60</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>14.7</td>
</tr>
<tr>
<td>40</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>24.8</td>
</tr>
</tbody>
</table>

**Table 4.3:** Data from Copper tape length test

Equation 4.2 was used to calculate the charge rate for the different lengths, the result can be found in table 4.4.

<table>
<thead>
<tr>
<th>Length [cm]</th>
<th>volts per second [V/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.373</td>
</tr>
<tr>
<td>80</td>
<td>0.282</td>
</tr>
<tr>
<td>60</td>
<td>0.201</td>
</tr>
<tr>
<td>40</td>
<td>0.120</td>
</tr>
</tbody>
</table>

**Table 4.4:** Different lengths chosen of the copper tape
4.1.3 Comparison

Figure 4.1: Diagram of the charging time for the different lengths of the harvesting shield

Figure 4.1 shows the time required to charge a 10 μF capacitor from 3 V to 6 V depending on the length of the harvesting shield.

Figure 4.2: Diagram of the charge rate for the different lengths of the harvesting shield

Figure 4.2 shows the charge rate in volts per second depending on the length of the harvesting shield.
4.2 Discharge curve of the storage capacitor

Fig. 4.3 shows the behavior of the storage capacitor when it reaches its maximum value of 8.73 V and discharges. The bend at 24.8 ms on the blue curve is when the wireless data transmission is complete and the data ready pin is set high, draining the storage capacitor over R2 as explained in section 3.4 and can be compared with the green curve which is discharge time of the circuit without the data ready pin connected to the base of Q3.

*Figure 4.3: Measurement of the discharge time for the whole circuit*
4.3 Different types of cables

In section 3.11 the setup for this test is described and fig. 4.4 and fig. 4.5 shows the resulting graphs. The charging rate of the two core cable can be calculated to $6V/12.6s = 0.48V/s$ and for the three core $6V/28.8s = 0.21V/s$.

**Figure 4.4:** Measurement of the charging curve for the different cables

**Figure 4.5:** Measurement of the charging curve for the different cables
4.4 Power consumption

In this section, the result of the measurements related to power consumption is presented.

4.4.1 Dynamic current consumption

The test setup is described in section 3.3.4.2. In fig. 4.6 below one can see that the width of the current drain is 1.6 ms. This width matches the measured time consumption very well. The height can be seen in fig. 4.7 and is around 100 mV. Using Ohm’s law gives: \( I = \frac{V_{ab}}{Rm} \), \( 100mV/10Ohm = 10mA \).

\[ \Delta: 12mV \]
\[ \Delta: 1.60ms \]
\[ @: 52mV \]

Figure 4.6: Measurement of the dynamic current consumption width result
Figure 4.7: Measurement of the dynamic current consumption height result
4.5 Current sensing circuit

In this section follows measurements of the different stages in the current sensing circuit as seen in fig. 3.16. All the tests were done on a load that consumes about 800 W.

![Figure 4.8: Measurement of the current sensing circuit with no DC offset capacitor](image)

Figure 4.8: Measurement of the current sensing circuit with no DC offset capacitor
**Figure 4.9:** Measurement of the current sensing circuit with 100 nF DC offset capacitor.
Figure 4.10: Measurement of the current sensing circuit with 10 nF DC offset capacitor
**Figure 4.11:** Measurement of the current sensing circuit with 100 nF DC offset capacitor and the rectifier circuit added

**Figure 4.12:** Measurement of the current sensing circuit with 100 nF DC offset capacitor, rectifier circuit and filter capacitor added
Figure 4.13: Measurement of the current sensing circuit with 10 nF DC offset capacitor, rectifier circuit and filter capacitor added.

Figure 4.14: Measurement of the current sensing circuit with 10 nF DC offset capacitor, rectifier circuit and filter capacitor added, zoomed in.
4.5.1 Time consumption for a wireless data transmission

One can clearly see in fig. 4.15 that the VCC channel is set high at time zero. About 7.61 ms later the DR pin channel is set high, this indicates that the time required to perform the transmission of one data package is about 7.61 ms.
4.5.2 Time consumption for the whole system

**Figure 4.18: Measurement of the time consumption for the whole system**

<table>
<thead>
<tr>
<th>Time current on [ms]</th>
<th>Time current off [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.811</td>
<td>23.821</td>
</tr>
<tr>
<td>22.815</td>
<td>23.205</td>
</tr>
<tr>
<td>22.807</td>
<td>23.204</td>
</tr>
<tr>
<td>22.797</td>
<td>23.212</td>
</tr>
<tr>
<td>22.861</td>
<td>23.204</td>
</tr>
<tr>
<td>22.602</td>
<td>23.206</td>
</tr>
<tr>
<td>22.815</td>
<td>23.203</td>
</tr>
</tbody>
</table>

**Table 4.5: Measurements of the time consumption for the whole system**
4.5.3 Placement of the hall effect sensors

Fig. 4.19 shows the results when the hall effect sensors were placed at different locations on the cable. The blue curve represents a perfectly placed cable, the red curve a cable that have been rotated a bit from the optimal placement and the green curve shows the worst case scenario.

**Figure 4.19:** Measurement of the sensors placed at different locations on the multicore cable
**Figure 4.20:** Measurement of the the hall effect sensors faced at different directions towards the cable.
4.6 Long term testing

In section 3.9 the test setup is described. The test was left running overnight with the load turned off, the result can be found in table 4.6. The next day the test was left running for several hours with the load turned on, the result can be found in table 4.7. A 200 μF capacitor was used in this test. The logging device is also programmed to measure the time between two packages and for a 300 cm long aluminum harvesting shield with a 200 μF storage capacitor the time is around 90 seconds.

<table>
<thead>
<tr>
<th>Day</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>435</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>420</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>416</td>
</tr>
</tbody>
</table>

*Table 4.6: Result of the long term off test*

<table>
<thead>
<tr>
<th>Day</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>154</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>160</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 4.7: Result of the long term on test*
5.1 Discussion regarding the test results

5.1.1 Harvesting material

Aluminum foil and copper tape were compared in this test, and by looking at the results one can clearly see that the charging rate of the copper tape is faster than of the aluminum foil. One of the reasons is that it is easier to get a close connection between the copper tape and the isolation of the cable which minimizes the distance between the harvesting shield and the conductors. The aluminum foil, on the other hand, has a tendency to wrinkle, creating some air pockets between the cable isolation and the foil which will increase the distance between the harvesting shield and the conductors.

5.1.2 Harvesting shield length

The result of this test is presented in section 4.1. The result is pretty straightforward, longer harvesting shield equals faster charging rate. If one studies the diagram in fig. 4.2 one can quickly draw the conclusion that the relation between the length of the harvesting shield and the charging rate is quite linear.

5.1.3 Different cables

The figures fig. 4.4 and fig. 4.5 clearly shows that the two core cable has a faster charging rate than the three core cable. The thickness of the isolation of the cable is an important factor in this case. As one can see in fig and fig. 3.27 the isolation in the three core cable is thicker than the one of the two core cable.
5.1.4 Dynamic current consumption

Section 4.4 presents the result of the test. The result of the pulse width, 1.6ms matches the measured time consumption very well. And the height that represents 10 mA is close to the specified current of 9 mA. However the results were not as good as expected, we expected a more clear and detailed curve with less ripple. Maybe a smaller resistance of the resistor Rm would have generated a better result, but 10 Ω was the smallest resistor we had access to.[21]

5.1.5 Placement of the hall effect sensors

Because of the non-invasive current sensing approach, taking advantage of the asymmetric properties of a multicore power cable with hall effect sensors are used, the placement of the sensor towards the cable showed to be crucial. The different outputs when turning the cable around even a few degrees are showed in fig 4.19 and can cause big changes on the output.

In fig 4.20 one can see how alternating the direction of which the hall effect sensors are facing the cable affect the output. The difference in output does not change drastically, but it is enough to consider when designing a PCB.

5.2 Discussion regarding the method

In the planning phase of the project, a project plan and a time plan, including tasks with different priorities and mile stones, was formed. This project plan was very helpful, although one thing got left out. The measurements were not fully planned ahead in the project planning phase, which sometimes led confusion and delays.

The system was built on a breadboard with long jumper cables connecting the different components. This setup was used for some of the tests. Later on when the functionality was confirmed, every component were soldered to a prototype card. Some tests were done with this new prototype, but there was not enough time to redo all of the tests. Hence the test results may differ a bit because of bad connections and/or long signal cables. For even more accurate results, one could design a PCB for the system.

Some of the measuring instruments used were cheap and of bad quality. The multimeter used was of a very basic and cheap model. The result might be a bit of because of this, especially the low current measurements. The logic analyzer used was a cheap USB based model. The results from the logic analyzer however seemed accurate compared to the results from the more expensive oscilloscope.

The system was tested to verify that the functional requirements that was set up in the beginning of the project were met. These test were performed in an open space environment so that interference of any kind that could affect the verification of the design was minimized. Since there was not much time left at this phase of the project, the system was never tested in the different environments.
that it might would have been placed in for its intended use. This means that the report are lacking data from how the functionality are affected when for example placing the system behind a stove in the kitchen.

5.3 Conclusions

This thesis has proven the concept of using energy harvested from the electric field of a cable to power a current sensor and an RF transmitter to work, but how realistic is it to use this concept in a product? The product in mind, a surveillance system for fire hazardous consumer electronics needs to be quite responsive. For example if one turns off the oven one would want the system to update almost instantly, if the system displays the old status of the oven too long the user might be tricked and the system loses its purpose. For our prototype, the response time is in the worst case around 90 seconds even with a ridiculously long harvesting shield of 300 cm. This has to be considered to be too slow. The main reason for the slow response time is the energy consumption of the current sensor. If one would find a better, less energy consuming method of detecting if there is current flowing through a cable, this concept might work. But for our prototype a better option for a power source would be a battery. Even if the idea of having a system where you don’t have to worry about changing the battery sounds promising, the downside, the slow response time, is too big.

5.4 Future work

Even though in this thesis work we managed to come up with a prototype that provided a fully functional solution, there are areas in which the design of the system can be improved.

5.4.1 Improving the energy harvesting circuit

Our design of the harvesting circuit has a flaw. When the microcontroller is done, it kills the circuit by shorting the capacitor over a resistor. This is done in order to release the latch so the storage capacitor can be charged once again. This method wastes a lot of energy because the storage capacitor is drained to about 1.5 V, but the circuit only needs to drain it to about 5 V. The remaining 3.5 V is only drained in order to reset the latch. Fig. 5.1 illustrates the charging behavior of our circuit, while fig 5.2 shows the optimal charging behaviour.
5.4.2 Alternative power source

Although the sensor node was able to run only on harvested energy, the output of the sensor was not produced as fast as wanted for this application. To run the system on a battery instead, some smaller adjustments to the circuit is necessary.

5.4.3 Multi sensor node system

While having designed a functional sensor node, we did not have time to investigate the possibility of having multiple sensor nodes connected in one network. One desirable feature of our sensor node system would to be able to add more sensor nodes to the network after the network have been established.

Figure 5.1: Illustration of the charging behavior of our design

Figure 5.2: Illustration of the optimal charging behavior
5.4.4 Improved receiver

The receiver designed for this application is very simple and only has two LEDs which are used as an indicator to display the status of the sensor node since for the moment, we only have one sensor. When having multiple sensors in the same network, some form of graphical interface might be required in order to display the status of all the sensors. Even though this will require both more hardware and software, the receiver does not have any constraints on its size or power consumption. A good idea might be to make the receiver compatible with an already well-known platform, for example, a Raspberry Pi.

As a complement to the improved receiver with a graphical interface, a smartphone application that can be connected to the receiver could be developed. By having this portable version of the receiver, you can get important notifications even if one is not at home.
Appendix
Below follows the code for the transmitter. After some initialization, the microcontroller waits for the ADC value to reach 2 V and then starts to sample 200 values of the ADC, removing the value corresponding to a 2.45 V offset, taking the absolute value and adding it to a total value. The total value gets divided by the amount of samples at the end, producing an average of the 200 samples. Depending on whether the microcontroller is in programming mode or not, the value is either written to the EEPROM used for reference, or used as the measured value from the sensor. The RF-transceiver are then powered up and the transmitter sends current ON or current OFF to the receiver depending on the value.

```c
#include <avr/io.h>
#include <avr/eeprom.h>
#define F_CPU 1000000UL  // 1 MHz
#include <util/delay.h>
#define NOP 0xFF
#define BIT(x) (1 << (x))
#define SETBITS(x,y) ((x) |= (y))
#define CLEARBITS(x,y) ((x) &= ~(y))
#define SETBIT(x,y) SETBITS((x), (BIT((y))))
#define CLEARBIT(x,y) CLEARBITS((x), (BIT((y))))
#define W 1
#define R 0
#define NRF905_CALC_CHANNEL(f, b) (((f) / (1 + (b)>>1)))
```
- 4224000000UL) / 100000UL)
// Workout channel from frequency & band

void InitSPI(void);
char WriteByteSPI(unsigned char);
uint8_t readreg ();
void w_tx_address ();
void rfinit ();
void portinit ();
void w_tx_payload (uint8_t);
void adc_init();
uint16_t adc_read();

int main(void)
{
    uint16_t res = 0;
    uint16_t brus = 0;
    int val = 0;
    uint32_t sum = 0;
    int on = 0;

    adc_init();
    portinit();
    InitSPI();
    CLEARBIT(PORTA,6); //tx_en
    CLEARBIT(PORTA,4); //CE low
    CLEARBIT(PORTA,7); //pwr

    val = adc_read(); //First adc value might be trash, throw it
    _delay_ms(2);
    val = adc_read();
    while (val < 650) //Wait for signal to hit 2v
    {
        val = adc_read();
    }

    for(int i = 0; i < 200; i++) // Sample 200 times
    {
        val = adc_read() - 760; //Remove 2.45v offset
        if (val <0){
            val=0-val; //Make positive
        }
        sum = sum + val; //Add sample to sum
    }
res = sum / 200;

if(PINB & (1<<PB6)) //Check programming switch
{
    eeprom_update_word((uint16_t*)0x28, res);
    //If on write res to eeprom
} else
{
    brus = eeprom_read_word((uint16_t*)0x28);
    //Off, read brus from eeprom

    if (res > (brus+13))
    {
        on = 1;
    } else{
        on = 0;
    }
    rfinit(); //2.3ms
    CLEARBIT(PORTA,4); //CE low
    SETBIT(PORTA,7); //pwr
    w_tx_address();
    if(on == 1)
    {
        w_tx_payload(0xA3);
    } else if(on == 0)
    {
        w_tx_payload(0x03);
    }
    SETBIT(PORTA,6); //tx en
    SETBIT(PORTA,4); //CE high
    _delay_us(50);
    CLEARBIT(PORTA,4); //CE low
}

void InitSPI(void)
{
    USICR |= (1<<USIWM0)|(1<<USICS1)|(1<<USICLK);
    //3-wire mode, clk settings
    SETBIT(PORTA, 5); //CSN high
}
char WriteByteSPI(unsigned char cData)
{
    USIDR = cData;

    USISR |= (1<<USIOIF);

    while ((USISR & (1<<USIOIF)) == 0)
    {
        USICR |= (1<<USITC); //toggle sck
    }

    return USIDR;
}

uint8_t readreg()
{
    uint8_t reg;
    CLEARBIT(PORTA,5);
    WriteByteSPI(0x19);
    reg = WriteByteSPI(NOP);
    SETBIT(PORTA,5);

    return reg;
}

void w_tx_address()
{
    CLEARBIT(PORTA,5);
    WriteByteSPI(0x22);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    SETBIT(PORTA,5);
}

void rfinit()
{
    uint16_t chan = NRF905_CALC_CHANNEL(433200000UL,0x00);
    CLEARBIT(PORTA,5);
    WriteByteSPI(0x00); //write
    WriteByteSPI(chan);
    WriteByteSPI(0b00000000);
WriteByteSPI(0b00100010);
WriteByteSPI(0b00000001);
WriteByteSPI(0b00000001);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
SetBit(PORTA,5); // cs
ClearBit(PORTA,5); // tx address
WriteByteSPI(0x22);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
WriteByteSPI(0xE7);
SetBit(PORTA,5);

ClearBit(PORTA,5); // clear DR
WriteByteSPI(0x24);
WriteByteSPI(NOP);
SetBit(PORTA,5);
SetBit(PORTA,7); // pwr up
}

void portinit ()
{
    DDRB |= (1<<PB2) | (1<<PB1); // SCK, MISO out
    DDRA |= (1<<PA5) | (1<<PA4); // CSN, CE out
    DDRA |= (1<<PA7);
    ClearBit(PORTA,7); // pwr_down
    DDRA |= (1<<PA6); // tx_en
    ClearBit(PORTA,6);
    DDRA &= ~(1<<PA3); // DR pin
    ClearBit(PORTA,3);
    DDRB &= ~(1<<PB0); // MOSI input
    PORTB |= (1<<PB0);
    DDRB &= ~(1<<PB6); // eeprom
}

void w_tx_payload (uint8_t payload)
CLEARBIT(PORTA, 5);
WriteByteSPI(0x20);
WriteByteSPI(payload);
SETBIT(PORTA, 5);
}

void adc_init()
{
  ADMUX = (1<<REFS0);  //AREF = ext
  ADCSRA = (1<<ADEN)|(1<<ADPS1);  //Adc enable, prescale 4
}

uint16_t adc_read()
{
  ADCSRA |= (1<<ADSC);
  while(ADCSRA & (1<<ADSC));
  return (ADC);
}
Below follows the code for the receiver. After some initialization, the microcontroller waits for incoming data from the transmitter. When data have arrived, a red or a green LED is lit up, depending on the received result.

```
#include <avr/io.h>
#define F_CPU 1000000UL // 1 MHz
#include <util/delay.h>
#define NOP 0xFF
#define BIT(x) (1 << (x))
#define SETBITS(x,y) ((x) |= (y))
#define CLEARBITS(x,y) ((x) &= (~y))
#define SETBIT(x,y) SETBITS((x), (BIT((y))))
#define CLEARBIT(x,y) CLEARBITS((x), (BIT((y))))
#define W 1
#define R 0

#define NRF905_CALC_CHANNEL(f, b) ((((f) / (1 + (b>>1))) - 422400000UL) / 100000UL)
// Workout channel from frequency & band

void InitSPI(void);
char WriteByteSPI(unsigned char);
uint8_t readreg ();
void rfinit ();
```
void portinit();
uint8_t r_rx_payload();

int main(void)
{
    portinit();
    InitSPI();
    _delay_ms(1);
    rfinit();
    _delay_ms(3);

    while(1){
        SETBIT(PORTA, 4); // TRX_CE
        _delay_ms(50);
        while(!(PINA & (1<<PA3)));
        CLEARBIT(PORTA, 4);
        _delay_ms(1);
        if (r_rx_payload() == 0xA3)
        {
            SETBIT(PORTB, 6);
            CLEARBIT(PORTB, 5);
        }
        else
        {
            SETBIT(PORTB, 5);
            CLEARBIT(PORTB, 6);
        }
        _delay_ms(1);
    }
}

void InitSPI(void)
{
    USICR |= (1<<USIWM0)|(1<<USICS1)|(1<<USICLK);
    //3-wire mode, clk settings
}

char WriteByteSPI(unsigned char cData)
{
    USIDR = cData;

    USISR |= (1<<USIOIF);

    while ((USISR & (1<<USIOIF)) == 0)
    {
        USICR |=(1<<USITC); //toggle sck
return USIDR;
}

uint8_t readreg ()
{
    uint8_t reg;
    CLEARBIT(PORTA,5);
    WriteByteSPI(0x19);
    reg = WriteByteSPI(NOP);
    SETBIT(PORTA,5);

    return reg;
}

void rfinit ()
{
    uint16_t chan = NRF905_CALC_CHANNEL(433200000UL,0x00);
    CLEARBIT(PORTA,5);
    WriteByteSPI(0x00); //write
    WriteByteSPI(chan);  //byte 0 channel
    WriteByteSPI(0b00001100);  //byte 1
    WriteByteSPI(0b00100010);  //byte2
    WriteByteSPI(0b00000001);  //byte3
    WriteByteSPI(0b00000001);  //byte4
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0b11011000);
    SETBIT(PORTA,5);
    CLEARBIT(PORTA,5);  // tx address
    WriteByteSPI(0x22);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    WriteByteSPI(0xE7);
    SETBIT(PORTA,5);
    CLEARBIT(PORTA,5);  // clear DR
    WriteByteSPI(0x24);
    WriteByteSPI(NOP);
    SETBIT(PORTA,5);
    SETBIT(PORTA,7);    //pwr up
void portinit ()
{
    DDRB |= (1<<PB2) | (1<<PB1); // SCK, MISO out
    DDRA |= (1<<PA5) | (1<<PA4); // CSN, CE out

    DDRB &= ~(1<<PB0); // MOSI input
    PORTB |= (1<<PB0);

    DDRB |= (1<<PB6); // led on
    CLEARBIT(PORTB, 6);

    DDRB |= (1<<PB5); // led2
    CLEARBIT(PORTB, 5);

    DDRA |= (1<<PA7);
    CLEARBIT(PORTA, 7); // pwr_down
    _delay_ms(5);

    DDRA &= ~(1<<PA3); // DR pin
    CLEARBIT(PORTA, 3);

    SETBIT(PORTA, 5); // CSN high
    CLEARBIT(PORTA, 4); // CE low
}

uint8_t r_rx_payload ()
{
    uint8_t payload;
    CLEARBIT(PORTA, 5);
    WriteByteSPI(0x24);
    payload = WriteByteSPI(NOP);
    SETBIT(PORTA, 5);

    return payload;
}


List of Figures

2.1 Block diagram of a typical energy harvesting circuit ............... 5
2.2 Illustration of the electric field of a point charge [8] ............ 6
2.3 Illustration of the magnetic field of a moving charge [6] ........ 6
2.4 Symbol of the operational amplifier .............................. 9
2.5 Characteristics of an operational amplifier without feedback .... 10
2.6 Circuit diagram of an operational amplifier with negative gain .. 10
2.7 First order high pass filter with negative gain ................... 11
2.8 Characteristics of a first order high pass filter with negative gain 12
2.9 First order low-pass filter with negative gain ........................ 13
2.10 Characteristics of a first order low-pass filter with negative gain 14
2.11 Cross section of one three core and one two core cable.[5] .... 14
2.12 Illustration of the sampling process of an analog signal [7] ....... 15
2.13 Illustration of an assembled data packet in ShockBurst™ TX mode 16

3.1 Block diagram of the system overview .............................. 18
3.2 Flowchart of the system ............................................. 18
3.3 Circuit diagram of the energy harvesting circuit .................... 19
3.4 Copper tape used as harvesting shield .............................. 20
3.5 Aluminum foil used as harvesting shield .......................... 20
3.6 Energy harvesting circuit simulated in multisim .................... 21
3.7 Simulation result of the energy harvesting circuit in multisim ...... 21
3.8 Symbol for the linear voltage regulator ............................ 22
3.9 Circuit diagram of the transmitter circuit .......................... 24
3.10 nRF905 operating modes ............................................ 25
3.11 Flowchart for the RF transmitter .................................... 26
3.12 Circuit for measuring the current consumption of the nRF905 .. 28
3.13 Circuit for measuring the current consumption of the nRF905 and ATtiny861 ....................................................... 29
3.14 Circuit diagram of the wireless data transmission node together with the energy harvesting circuit ................................. 30
3.15 Circuit for measuring the current consumption of the NTE1904 voltage regulator .................................................... 31
3.16 Circuit diagram of the full current sensor circuit .................... 33
3.17 Circuit diagram of the optimized current sensor circuit .......... 35
3.18 Flowchart of the current sensing algorithm ........................ 37
3.19 Circuit for measuring the current consumption of the current sensor
3.20 Picture of the sensor node prototype
3.21 Circuit diagram of the final circuit
3.22 Circuit diagram of the energy harvesting circuit together with the wireless data transmission node connected to an oscilloscope
3.23 Waveform illustrating the behavior of the energy harvesting circuit
3.24 Picture of the receiver module connected to the logging device
3.25 Circuit diagram for the receiver module
3.26 Connections between the Arduino and the receiver
3.27 Cross section of two and three core cable
3.28 Test circuit for different cables

4.1 Diagram of the charging time for the different lengths of the harvesting shield
4.2 Diagram of the charge rate for the different lengths of the harvesting shield
4.3 Measurement of the discharge time for the whole circuit
4.4 Measurement of the charging curve for the different cables
4.5 Measurement of the charging curve for the different cables
4.6 Measurement of the dynamic current consumption width result
4.7 Measurement of the dynamic current consumption height result
4.8 Measurement of the current sensing circuit with no DC offset capacitor
4.9 Measurement of the current sensing circuit with 100 nF DC offset capacitor
4.10 Measurement of the current sensing circuit with 10 nF DC offset capacitor
4.11 Measurement of the current sensing circuit with 100 nF DC offset capacitor and the rectifier circuit added
4.12 Measurement of the current sensing circuit with 100 nF DC offset capacitor, rectifier circuit and filter capacitor added
4.13 Measurement of the current sensing circuit with 10 nF DC offset capacitor, rectifier circuit and filter capacitor added
4.14 Measurement of the current sensing circuit with 10 nF DC offset capacitor, rectifier circuit and filter capacitor added, zoomed in
4.15 Measurement of the total transmission time
4.16 Measurement of the standby mode time
4.17 Measurement of the transmission mode time
4.18 Measurement of the time consumption for the whole system
4.19 Measurement of the sensors placed at different locations on the multicore cable
4.20 Measurement of the the hall effect sensors faced at different directions towards the cable

5.1 Illustration of the charging behavior of our design
5.2 Illustration of the optimal charging behavior
List of Tables

3.1 Comparison of suitable RF transceiver devices [14] [22] [25] . . . . 23
3.2 Comparison of suitable microcontrollers . . . . . . . . . . . . . . 24
3.3 Settings of the nRF905 . . . . . . . . . . . . . . . . . . . . . . . . . 25

4.1 Data from aluminum foil length test . . . . . . . . . . . . . . . . 50
4.2 Different lengths chosen of the aluminum foil . . . . . . . . . . 50
4.3 Data from Copper tape length test . . . . . . . . . . . . . . . . . 51
4.4 Different lengths chosen of the copper tape . . . . . . . . . . . 51
4.5 Measurements of the time consumption for the whole system . . 63
4.6 Result of the long term off test . . . . . . . . . . . . . . . . . . . . 66
4.7 Result of the long term on test . . . . . . . . . . . . . . . . . . . . 66
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