Autonomous battery less sensor for IoT applications in Smart Buildings

Ambient RF Harvesting in Office Environment for IoT Sensor

by

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Preface

This report discusses one part of a project consisting of three parts. The goal of the project is to design a battery less sensor powered by RF energy fields present in an office environment. The sensor is able to measure the temperature and is able to communicate wirelessly using a low power communication protocol. In this project the use case of a building will be explored, where the climate and lighting of different rooms can be adapted, be monitored and be adjusted remotely. Commissioned by the dean of faculty EEMCS of the University of Technology Delft prof. dr. John Schmitz this project has started as a Bachelor Graduation Project for the BSc. Electrical Engineering. This project was assigned to a group consisting of two students per subgroup, six students in total.

This part treats the harvesting part, which scavenges the RF power out of the ether and delivers it to the rectifier to convert and store the energy. First the spectrum has been analyzed to determine the most suitable frequency band. An antenna has been designed to harvest as much power at the chosen frequency. Therefor the reflection coefficient is taken as quantification of performance but also the efficiency of the antenna has to be taken into account. To make the power transfer from the antenna to the rectifier as efficient as possible, impedance's have to be matched. In this report, a Planar Inverted-F Antenna is designed to meet all the given requirements.

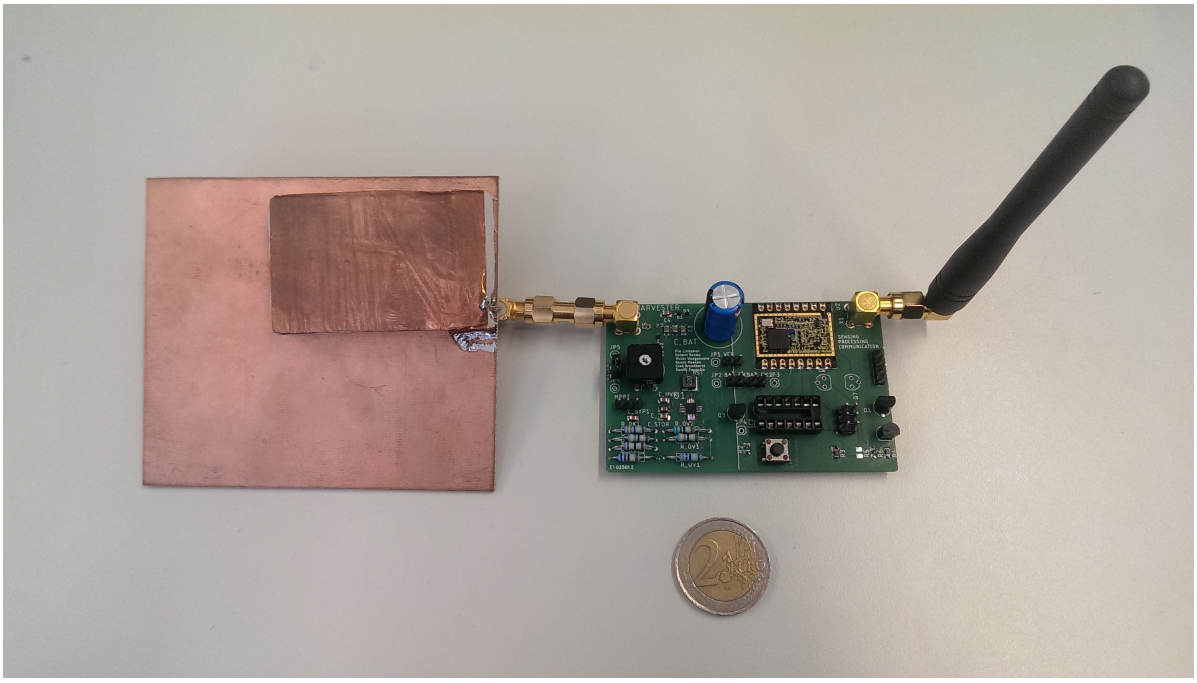

Figure 1: Picture of the end prototype

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1
Introduction

A lot of electronic devices today consume a lot of energy, which is often stored in a battery. This battery can be recharged with a battery charger or can be replaced by another battery. Today a lot of electronic devices can be charged wirelessly by using inductive coupling, capacitive coupling or magnetodynamic coupling. Applications of these techniques are charging mobile phones, electrical toothbrushes, biomedical microsystems [1] and even electrical driven cars can be charged wirelessly by a coil in the transmitter with a varying electric current passing through which produces a current in a receiver coil placed in the car itself.[2]

These charging techniques are based on the experiments of inventor Nikola Tesla. He experimented with lighting a lamp by using of resonant inductive coupling of two LC-circuits, varying the physical distance between the transmitter and the receiver. These experiments of Tesla have still impact on today's technology, like he wanted in his days:

> "As regards the production of light, some results already reached are encouraging and make me confident in asserting that the practical solution of the problem lies in the direction I have endeavored to indicate. Still, whatever may be the immediate outcome of these experiments I am hopeful that they will only prove a step in further developments towards the ideal and final perfection." - Nikola Tesla [3]

All these applications are dependent on an external energy source, but what if a device does not need a battery and can operate autonomously? One of the solutions is Radio-Frequency (RF) energy harvesting. An energy conversion technique where electromagnetic waves on ultra high frequencies (UHF), which are present almost everywhere in the air, are transformed into electric power. Billions of radio transmitters everywhere in the world are broadcasting RF energy, including mobile telephones, mobile base stations (GSM), television broadcast stations, radio broadcast stations and internet modules (WiFi/3G/4G). This RF energy can be harvested from ambient sources and can be used for wireless charging. With this technique a very low energy consuming device, like a temperature sensor, can operate without using a battery and can be placed everywhere.

1.1. Problem definition

RF-energy harvesting is a present-day technique which was not a common alternative for energy harvesting in the past. The reason for this was the availability of RF energy. A couple of years ago very little RF energy was available compared to now, due to the fact that today mobile phones are used more and more and internet becomes more important. At this moment some companies are experimenting with autonomous sensors, like NOWI-energy [4], Freevolt [5] and Powercast [6]. These products make use of RF energy harvesting to longer the lifetime of the battery of the device. The achievement of RF energy harvesting techniques is to have a device that does not need a battery and consumes only energy from electromagnetic waves on radio frequencies. This is very useful for all Internet-Of-Things (IoT) applications. Millions of sensors will be used for this technology, and one can imagine that it is not feasible to change the batteries of all these sensors every now and then or to pull cables everywhere to connect the sensors to the grid.

Therefore a solution will be presented. In this project a device will be designed that will power a temperature sensor with RF energy harvesting and communicate the data wirelessly to a base station, *without using a battery*. This base station will upload the data to "the cloud", where the data will be stored. This feature is necessary for the IoT-applications. An overview of the system can be seen on Fig. 1.1. To harvest the RF energy an antenna will be used and will be matched to a rectifier, which converts the ultra high frequency signal to DC. The energy will be stored in a capacitor and will be used to power the temperature sensor and the data processing unit, which collects the data and transmits it to a base station. With this system design no battery will be needed. The goal is to harvest as many energy as available and to use this energy as efficient as possible.

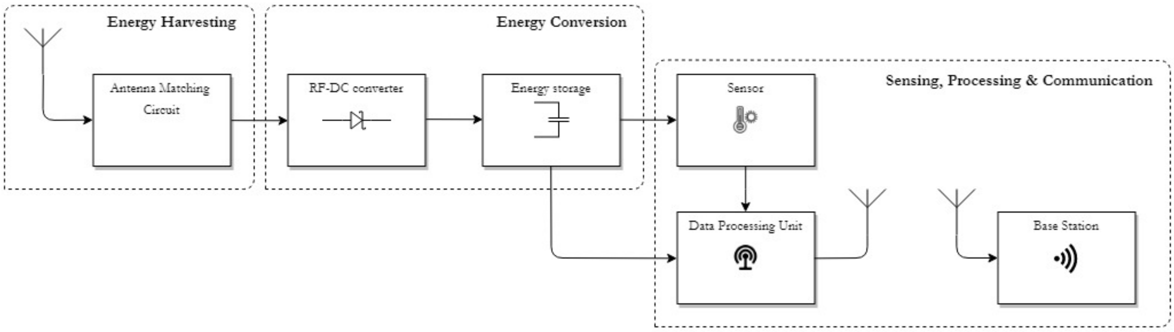

Figure 1.1: System overview

This device can be placed everywhere and will operate for an infinite time, without the need of substituting the battery every once in a while and without using many cables to provide the device with energy from an external energy source. With this device it is very easy to measure environmental parameters at every location if enough RF energy is available. By collecting all the data in "the cloud", these devices can be used in Smart Buildings: building automation. A category of control and communications technologies that link building systems that are typically controlled separately. This can be systems for electrical distribution, fire alarming, security, heating and air conditioning. [7] Our design will succeed if only one sensor can be powered by RF energy harvesting, without the use of a battery.

It is possible to design a system with these features, but the system is dependent on the available RF energy at the location where the device is placed. The level of ambient RF energy affects the frequency that the system can sense and communicate and also the functionality of the system. A reduction in RF energy means that the period between each time the data can be communicated increases and a minimum level of available energy has to be reached to convert the RF energy to a voltage level that can be used by our system. The efficiency of each subsystem quantifies the capability of that part. To achieve the best performance each of the subsystems have to be optimized and matched to each other. The performance of the whole system is best observed with the sense-and-communicate frequency.

2

Programme of Requirements

2.1. Requirements of whole system

The goal of this project is to build an *Autonomous battery less sensor for IoT-applications in Smart Buildings*. This chapter will present the requirements of the whole system and the special requirements for the subsystem discussed in this report.

2.1.1. Technical specifications

1-1 Cloud
The sensor should be an IoT-device, which means that it is connected to the cloud. This can be concretized as follows: the device must communicate its measured values to another device (base station or service) which on its turn will make the information available over internet. In other words, the device does not have to be directly connected to the internet per se, as long as its information becomes available on the internet.

1-2 Smart building
The device is intended for use in so called *Smart Buildings*. A Smart Building in this sense uses many sensors and actuators to control for example the climate (temperature, humidity, air quality) or security autonomously, so without the intervention of a human person [7].

1-3 Self powered
There should be no need to physically access the device on a regular basis. This means the device cannot use batteries, because they need replacement every now and then. Also, in order to be versatile and easy to place anywhere, the device should not use a wired power source. The device should therefore be able to extract energy from its environment and this should be done by the use of RF harvesting.

1-4 Measured quantity
For this project, it is sufficient to just measure ambient temperature. This should be possible with a precision of about 0.1 °C. Furthermore, the device must be designed in such a way that at a later stage, the temperature sensor could easily be replace with a different sensor (e.g. humidity or light intensity).

1-5 Integrity
The device should ultimately be used in a Smart Building, thus be connected to certain actuators in an autonomous fashion. It is therefore essential that the data produced by the device is correct. There must be a form of error checking, so that faulty data is discarded.

1-6 Redundancy
The device completely depends on ambient RF sources and in case these are non-existent or the power that can be extracted from them is too little, the device will be unable to function. This is acceptable and should be considered in the application of the IoT-sensors, they might not function from time to time due to lower levels of RF energy. Having many sensors in different locations obviously reduces the chance that no sensor in a certain vicinity functions, so this is a way to overcome the problem.

1-7 Production cost
The devices should be used on large scale, i.e. many sensors should be placed in a building. This requires that the production cost of a single sensor is limited and should not exceed €50.

1-8 Configuration
Either the device must be designed in such a way that no configuration is needed, i.e. it can just be placed somewhere and work right away. Otherwise, the device must have an interface so a serviceman can configure the necessary settings on site.

1-9 Security
The data coming from the device must be secured, so that it is not possible for anyone to interfere. It should not be possible to mimic the device, nor should the data be readable by anything other than the intended receiver.

2.1.2. Geometric specifications

2-1 Office Environment
The IoT-sensor will be designed for operation in an office environment. This office environment is considered to be on the mainland, i.e. to be covered by the GSM-network and not to be exposed to abnormal amounts of RF (e.g. near a microwave oven).

2-2 Location
The IoT-sensor will be designed for operation in the EU. Transmission of RF fields is regulated by the EU defined rules for RF transmission. Also the harvesting of RF is based on operating frequencies in the EU.

2-3 Dimensions
Since the IoT-sensor is designed for use in an office environment, the actual size of the sensor is of great importance. The sensor should not interfere with the architectural and constructive aspects of the Smart Building. The maximum size of the sensor should be somehow equal to that of a normal enterprise grade WiFi access-point. The maximum dimensions are therefore defined as 200x200x100 mm (LxWxH).

2.1.3. Environmental specifications

3-1 Water & dust resistance
The IoT-sensor is designed for indoor use only. Since office environments are known to be not extremely dusty only a case to protect the hardware to big objects is necessary. Therefore the case will comply to IP1X dust protection (protection against objects bigger than 50mm). And since the sensor is designed for indoor use only, it will comply to IPX0 water protection (no special protection) [8].

3-2 Operating temperature
Since the IoT sensor is designed for indoor use only, the operating temperature will be 0-40°C. Assuming that an office will always be above 0°C because it is indoors. The maximum temperature of +40°C gives the capability to measure in (relative) hot rooms, like server rooms.

3-3 Overvoltage & Brown-out
As the input power (RF power) fluctuates quite randomly over time, there might be moments where there is a lot of power available and moments where there is very little. The device must be protected for sudden high levels of power, so that the device is not damaged. Also, the device must be able to cope with very little amounts of power, it is okay if it just stops working until there is enough RF power again.

3-4 Orientation
Since the antenna for the RF harvesting, implemented on the IoT sensor, is direction-sensitive, the direction of installation will be important. The direction of installation will be defined by the antenna design, and therefore determined at installation.

3-5 Minimal available RF power
In order to be able to harvest energy from the RF waves available in the office environment, the amount of available power has to be at least -25 dBm.

2.2. Requirements of the subsystem

The overall system is a sensor that transmits its data to the LoRa network. The whole module is powered by an antenna that receives ambient GSM signals. These received AC signals get converted to a usable DC voltage. A limited amount of RF power is available in the air, due to regulations of the ICNIRP (International Commission on Non-Ionizing Radiation Protection)[9]. This means the whole module also has limited power available to function. Eventually the available power that can be delivered to the circuit is determined by the design of the harvesting antenna.

The antenna needs to be easily manufacturable, like a microstrip patch antenna. The size of the antenna may ideally also not be larger than 10 by 10 cm, since otherwise the antenna would be out of proportion with the rest of the module, and the module would not be easily placeable inside smart-buildings.

The antenna must be tuned to a frequency band where most RF energy is available. By means of analysis of the spectrum an insight in what frequency bands are densely occupied has to be obtained. The Friis transmission equation (2.1) has to be taken into account, which states the large attenuation at high frequencies. High frequencies mean small wavelengths, which have an exponential effect on the received power.

$$\frac{P_r}{P_t} = D_t * D_r * (\frac{\lambda}{4 * \pi * d})^2 \tag{2.1}$$

In order to get maximum power transfer, the antenna needs to be matched to the rectifying circuit. Maximum power transfer occurs when the impedance of the antenna equals the complex conjugate of the input impedance of the rectifier: $Z_{Ant} = Z_L^*$. The impedance of the antenna changes along the frequency axis. The impedance of an antenna over a specific bandwidth can be measured with a Vector Network Analyzer. This results in a Smith Chart which can be very useful when designing a matching circuit.

The antenna and matching circuit will be connected to a rectifying circuit. The circuit converts the AC received signal to a DC voltage. The diodes in the rectifier circuit that are used (SMS7630) have a threshold voltage of 140 mV which is needed for them to work properly [10]. The antenna needs to deliver enough voltage to the circuit such that the threshold voltage over the diodes is reached. This comes down to -25dBm that has to be delivered to the terminals of the rectifier circuit.

A summation of the requirements is as follows:

4-1 The antenna must not be larger than 10 by 10 cm.

4-2 The antenna has a VSWR of maximum 2 at 845 MHz.

4-3 The antenna should have a bandwidth of 30 MHz.

4-4 The reflection coefficient of the antenna should be at least -15 dB.

4-5 The impedance of the antenna should be matched to the impedance of the rectifier circuit of $Z = 68.18 - j * 306.09\Omega$.

4-6 The antenna should have an output power of -25dBm.

3

Design Process

This chapter elaborates the design process and explains the choices that are made. The process is divided into three sections, namely choosing frequency range, the antenna and the matching circuit.

3.1. Choosing frequency range

In order to harvest as much energy as possible, a frequency range has to be chosen where there is a maximum of RF power available. Different studies are done to look into the potentials of RF power harvesting[11], [12], [13], [14], [15]. For example, measurements were done in all London Underground stations to investigate the RF power density of these places and correlate the results with the geographical distribution and population density [16]. In Japan terrestrial TV broadcast are tested as RF power source [17]. [18] gives an overview of the current researches that are done in the field of RF harvesting. New measurements were done in the center of Boston to determine the frequency bands and sensitivity of ambient RF power. These studies focuses mainly on the outdoor applications and therefor the use of RF power in the street and public places.

The system that is designed has the requirement to operate in an office environment. In this environment measurements can be done to characterize the ambient RF power coming from the WiFi transmission. The resulting power varies between -40 dBm and -20 dBm in the region of 2.4GHz and 2.48GHz, which corresponds with the WiFi-frequencies[19]. These measurements are performed in a setup which places the receiver close to the WiFi transmitter.

Different frequencies are used in the RF spectrum which can be considered to be harvested in order to power the system. The bands which are used for GSM are 845MHz and 1800MHz. These bands are frequently used in office environment. Also the 2.4GHz band is a potential band as it is used for WiFi. WiFi has a large attenuation due to a limited transmission power of 100mW and its very high frequency. Therefor the 5GHz WiFi band also isn't suitable for harvesting RF power.

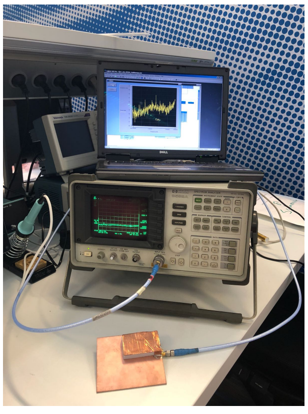

Figure 3.1: Measurement setup

A measurement setup (Fig. 3.1) is made to determine the actual RF power in an office environment. The spectrum analyzer is set to sweep the frequency bands which would be suitable for harvesting. The sweep is repeated in time, so the changes in received RF power can be measured. Different of the antennas are used to cover the whole spectrum.

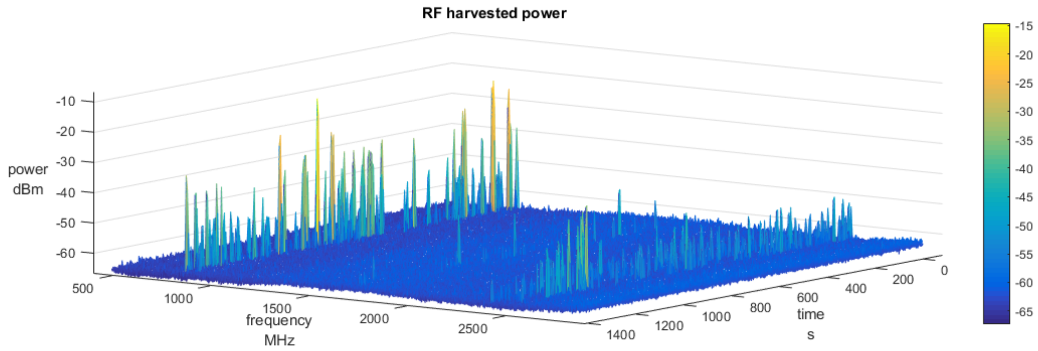

Figure 3.2: RF spectrum

In Fig. 3.2 the results are shown and the three bands can clearly be distinguished. Most of the power is transmitted in a band around 845MHz. This corresponds with the mobile phone communications which occurred during the measurement. It also shows that most of the GSM communication uses the 845MHz band instead of the 1800MHz band. The WiFi shows a continuous activity but to weak for reliable harvesting. The harvester should be located close to the WiFi router and therefor would be less mobile and independent. It was observed that the highest peaks occur around 845 MHz. That seemed obvious since this frequency band is used by Dutch telecom providers for GSM, LTE and UMTS [20].

3.2. Antenna

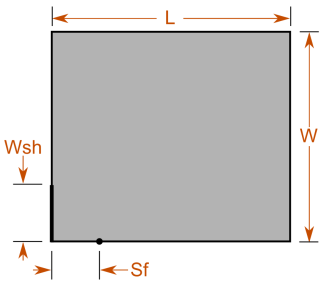

Figure 3.3: Top view of the PIFA

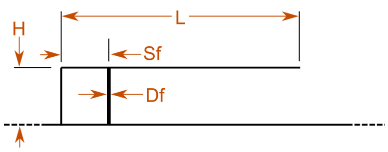

Figure 3.4: Side view of the PIFA

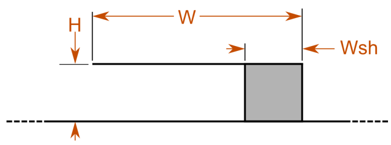

Figure 3.5: Front view of the PIFA

An antenna needs to be designed with good performance at the desired frequency. This frequency is chosen to be 845 MHz, as described in the previous section (section 3.1). A patch antenna or microstrip antenna is a convenient choice, since they are low cost and are easily fabricated [21]. Using a regular rectangular patch antenna, its length should be approximately one half of the wavelength to get resonance at the desired frequency. For 845 MHz, the wavelength is calculated in equation 3.1.

$$\lambda = \frac{c}{f} = \frac{3 * 10^8}{845 * 10^6} = 0.355\ meters. \tag{3.1}$$

Then, half the wavelength would mean a patch antenna with a length of 17 centimeters. This would be way to large for the module to still be easily placeable. For this reason a Planar Inverted-F Antenna (PIFA) is looked into. Sketches of the PIFA can be seen in Fig. 3.3, 3.4 and 3.5. Due to its shorting plate, the antenna becomes a quarter-wavelength antenna. This means the size of the antenna is reduced by approximately 50%.

The width of the shorting (Wsh) plate also has influence on the resonant frequency. The resonant length of the PIFA can be described by equation 3.2.

$$L + W - Wsh = \frac{\lambda}{4} \tag{3.2}$$

In the PIFA design, the patch and the ground plate are separated by air with relative permittivity $\epsilon_r = 1.00059$. Antenna design software Magus was used to design and tweak the PIFA. The dimensions of the designed PIFA can be found in Tab. 3.1. The surface size of the patch is 3.77 by 5.8 cm, which is smaller than the required 10 by 10 cm.

Table 3.1: Dimensions of designed PIFA

L	37.65 mm
W	58 mm
H	10.59 mm
Wsh	10.47 mm
Sf	5.93 mm
Df	1.18 mm

The PIFA has an omnidirectional radiation pattern. This means the antenna can receive signals from all directions. The downside of this pattern is that the gain of the antenna is lower. Due to the placement of the module in office environments the omnidirectionality is a wanted feature, since GSM signals will be originating from all different directions. A simulation of the radiation pattern can be seen in Fig. 3.7.

The impedance of the antenna should be close to 50Ω, so that it can easily be matched to the rectifier circuit later on. The impedance can be influenced by the placing of the feed relative to the shorting plate. With the PIFA with dimensions given in Tab. 3.1, the impedance at different frequencies can be seen in Fig. 3.6.

The reflection coefficient is a measure that gives information of the ratio of the wave that is received and the part of the wave that gets reflected, due to mismatch with the connected transmission line or system. The Voltage Standing Wave Ratio (VSWR) is a deduced measure of the reflection coefficient as can be seen in equation 3.3. The VSWR is thus a measure of how well the antenna is matched to the connected system. This means it is referenced to a specific value which is usually 50Ω. The reflection coefficient and VSWR connected to a 50Ω reference load can be seen in Fig. 3.8 and 3.9. The reflection coefficient and VSWR connected to a better matched 120Ω reference load can be seen in Fig. 3.10 and 3.11. When comparing these simulations with different loads, it can be seen that the reflection coefficient and VSWR are much lower for a better matched antenna, which means a much larger part of the received signal gets transmitted to the system. Also the frequency where the peak values occur gets shifted, which means the antenna can be tuned by the matching circuit.

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{3.3}$$

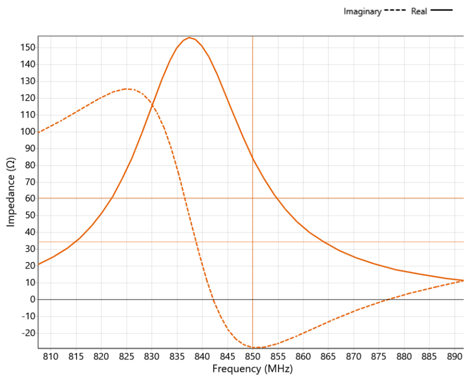

Figure 3.6: Expected impedance of designed PIFA

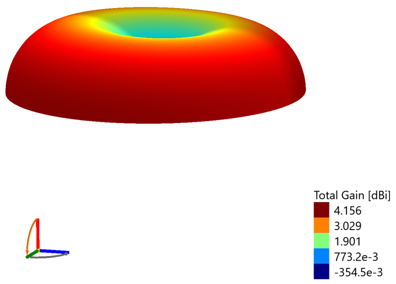

Figure 3.7: Simulated radiation pattern of designed PIFA

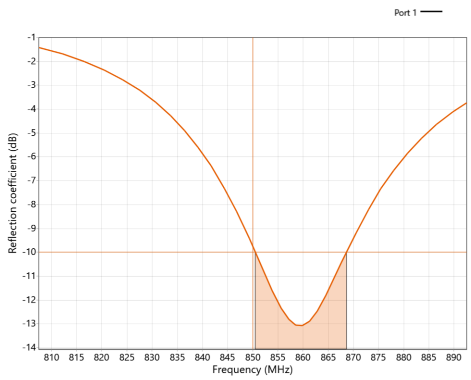

Figure 3.8: Simulated reflection coefficient as a function of frequency connected to a 50Ω reference load

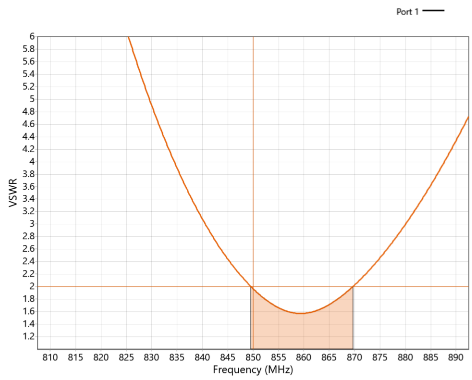

Figure 3.9: Simulated VSWR of the designed PIFA connected to a 50Ω reference load

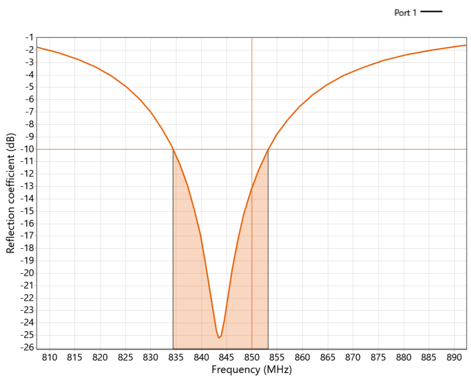

Figure 3.10: Simulated reflection coefficient as a function of frequency connected to a 120Ω reference load

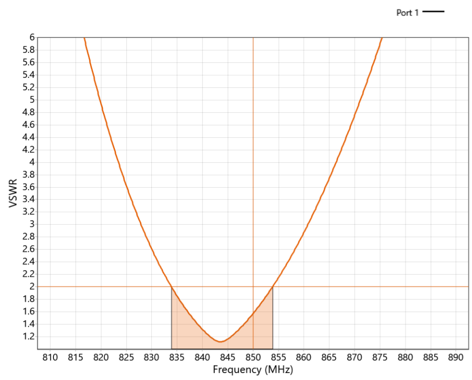

Figure 3.11: Simulated VSWR of the designed PIFA connected to a 120Ω reference load

3.3. Matching Circuit

In the previous section, the importance of the right load impedance was demonstrated. Matching the output impedance of the antenna to the input impedance of the rectifier will be crucial to the power transfer efficiency. Therefor the antenna was analyzed after being manufactured (as discussed in section 4.1.1 of the next chapter) on a vector network analyzer. These results (see section 4.1.2) were used to design a circuit that matches the impedance of the antenna to the input impedance of the rectifier at 845 MHz, which is $Z = 68.18 - j * 306.10\Omega$ [10].

The topology of the matching circuit is designed with just two components and a model of a transmission line. An inductor is placed in parallel to the ground with a capacitor in series. This circuit is shown in Fig. 3.12. Since a SMA connectors are used to connect the antenna to the PCB, a transmission line needs to be taken into account. A 4 cm long SMA adapter was used to connect the antenna to the circuitboard and can be considered a transmission line between antenna and circuitboard. The influence of the transmission line which is translated in electrical length is calculated at equation 3.4. The software program Advanced Design System (ADS) was used to determine the values for the inductor and capacitor of the matching circuit (Tab. 3.2). The simulation of the antenna connected to the matching circuit with reference load the impedance of the rectifier circuit can be seen in Fig. 3.13. Here can be seen that for the 845 MHz frequency, the antenna should be almost perfectly matched since the reactive part of the impedance is almost zero and the real part of the impedance is very close to one.

$$E = \frac{L}{\lambda} * 360\,\text{deg} = \frac{0.04}{0.355} * 360\,\text{deg} = 40.56\,\text{deg} \tag{3.4}$$

Table 3.2: Values of components for the matching circuit

L	26nH
C	0.9pF

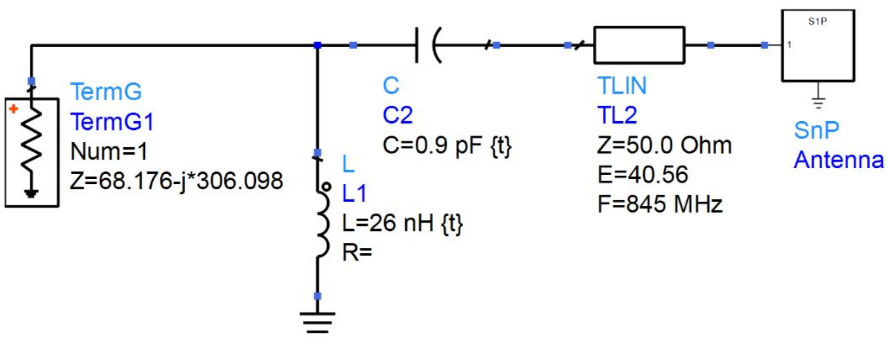

Figure 3.12: The designed matching circuit

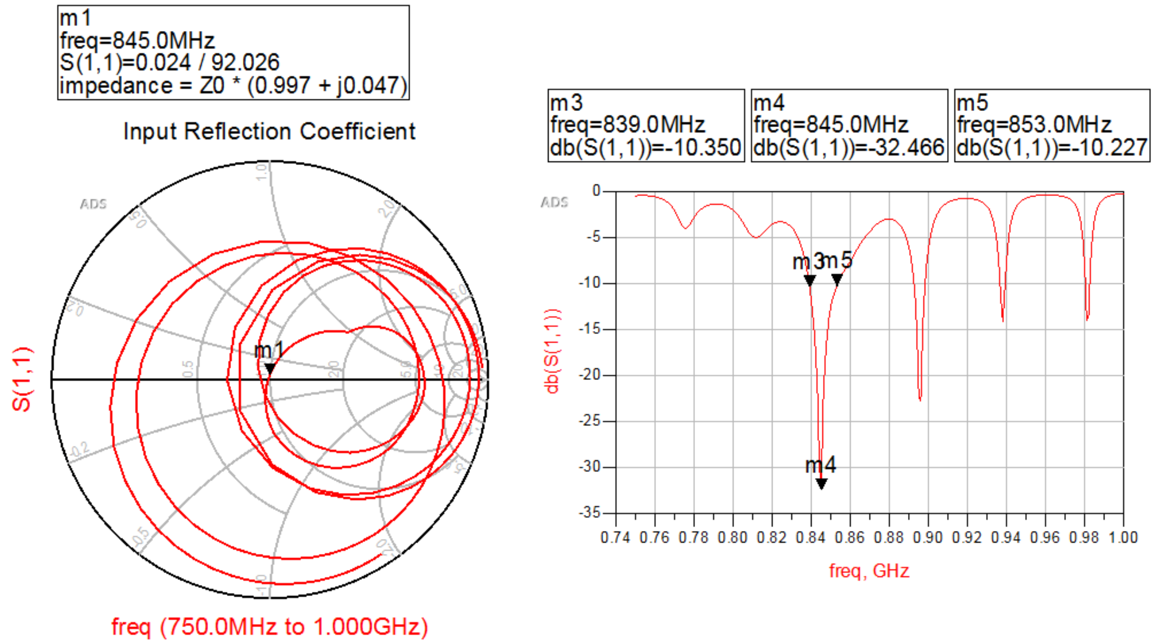

Figure 3.13: Smith Chart and reflection coefficient of the matched PIFA

4 Prototype Implementation

In this chapter there will be dealt with the implementation of an antenna which was designed in section 3.2 of the previous chapter. The performance and characteristics will be measured and compared to the requirements. The matching circuit will also be implemented as designed in section 3.3. The performance will be tested in combination with the manufactured antenna (Fig. 4.1). As can be seen in the part on conversion (Fig. 4.2 of [10], also found in appendix C), the final antenna is able to deliver sufficient voltage in order to surpass the threshold voltage of the Schottky diodes, which makes it able to rectify the AC signal.

Figure 4.1: Manufactured PIFA

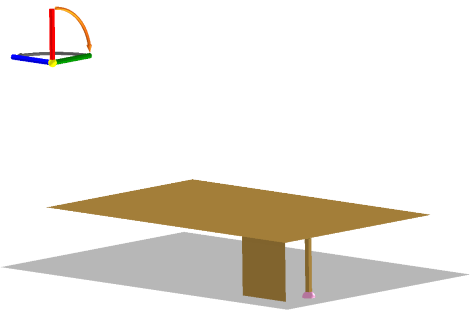

Figure 4.2: Model of the designed PIFA

4.1. Antenna

4.1.1. Implementation

The PIFA antenna has a simple design (Fig. 4.2) with few parts. The ground plane consists of a substrate with an even copper layer. The substrate is of FR4 material, with a relative permittivity of 4.2, however this has no effect on the antenna performance since the substrate is not in between the copper layers. The copper ground plane doesn't have to be of the same dimensions as the patch. By taking the ground plane larger than 0.2λ, the size of the ground plane has no significant impact on the resonant frequency [22]. The dimensions that are used for the ground plane and the placement of the patch on the ground plane can be found in Tab. 4.1 and Fig. 4.3.

All dimensions of the designed antenna are given the Tab. 3.1 of chapter 3. The patch is manufactured by cutting the right shape out of copper tape. To make the antenna more robust, the choice is made to implement an insulator between the ground plane and the patch instead of air. The insulator has a dielectric which is almost the same as air. The last important part is the feed between the patch and the connector. For this design an SMA connector is chosen which is connected to the feed coming from the patch and the ground plane. The SMA connector was necessary for doing measurements to the antenna.

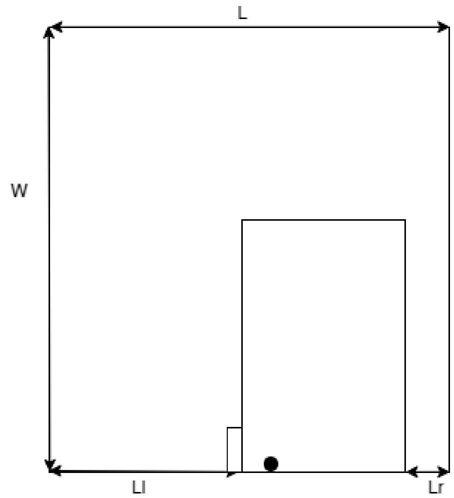

Figure 4.3: Implemented ground plane scheme

Table 4.1: Dimensions of the ground plane

L	87 mm
W	99 mm
Ll	45 mm
Lr	6 mm

4.1.2. Measurements

The SMA connector of the antenna can be connected to the Vector Network Analyzer (VNA). The VNA was used for measuring the scattering parameters (S-parameters) of the antenna. The S-parameters give information about the impedance of the antenna over a broad bandwidth as well as the reflection coefficient referenced to a 50Ω load. The results of VNA measurements can be seen in Fig. 4.4. The results of the VNA measurement resemble the simulated antenna characteristics a lot. These results are equal to an impedance of $Z_{ant} = 87.4 - j * 18.45$ at a frequency of 845MHz. Both have peaks exactly at 860 MHz and an equal bandwidth. This means the antenna is a successful realization of the designed PIFA.

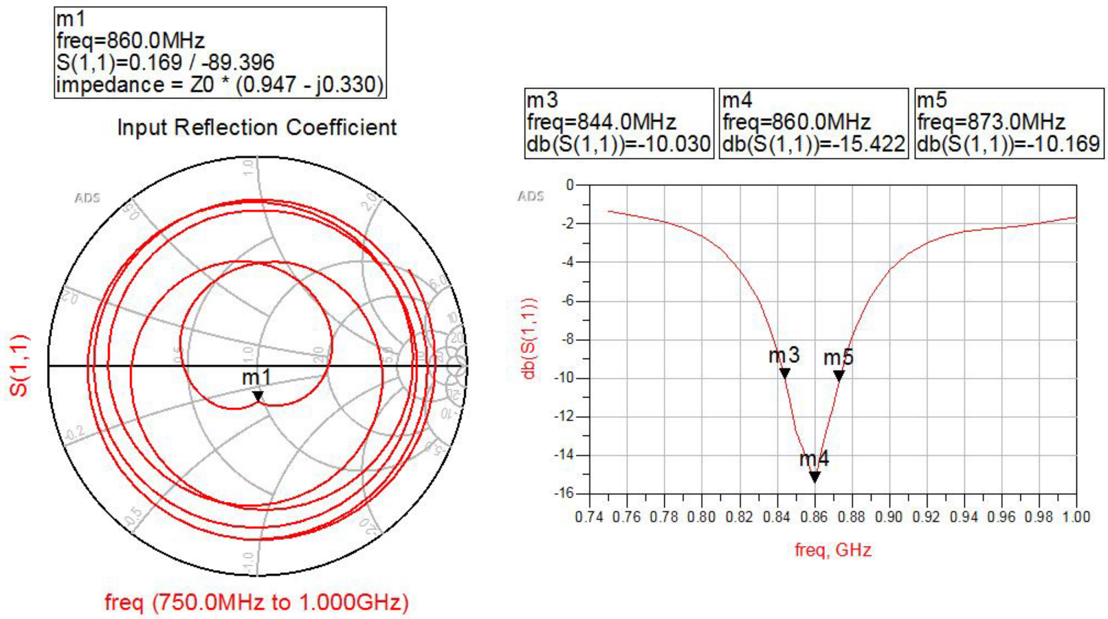

Figure 4.4: Smith Chart and Reflection Coefficient of the antenna referenced to 50Ω

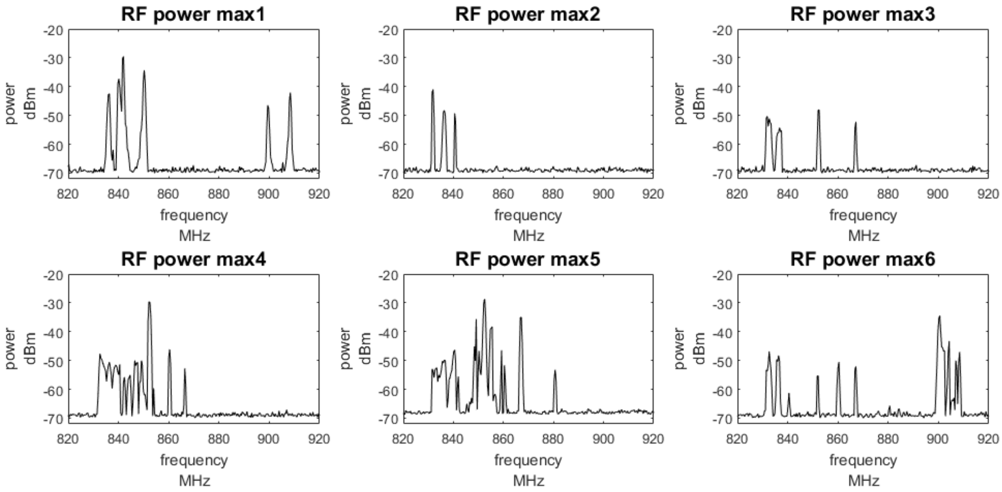

Figure 4.5: RF power max

The peak values of the chosen frequency are measured to determine the potential input power. By setting the spectrum analyzer up to hold the max value of each frequency during the duration of the measurement these peaks are found. This also implies that every received power which is less than the already measured power on a certain frequency is ignored. The result of six measurements can be found in Fig. 4.5. These measurements show that the peaks of the harvested RF power differ from each other. This dependency can be explained by whether or not there were mobile activities near the harvester. The maximum peaks which are measured are around the -25dBm, which meets with the requirements. The frequency at which the peaks occur also differ due to different mobile operators and up- and down-link. These peaks are all around 850MHz with a bandwidth of 30MHz.

4.2. Matching circuit

4.2.1. Implementation

The matching circuit is implemented on a PCB with the rest of the whole system [10],[23]. The PCB is designed connecting all the subsystems together in a compact, decent and clear way. Because of high frequencies, there are some requirements that have to be taken into account during the design process. The first one is the choice of components. These have to be adequate for the harvesting frequencies. To prevent transmission line effects in the paths of the PCB, the components before the rectifier have to be close to each other. The paths between these components have to be shorter than 10% of the wavelength (equation 3.1). This is in line with the maximum length of the paths equal to 3.5cm.

The PCB design is shown in Fig. 4.6. The matching circuit is clearly indicated with a red rectangle. Both the inductor as the capacitor can be differentiated as they have a circle around them. For the connection to the antenna a SMA connection is used. This also has an advantage that the whole system can be analyzed with a VNA. The subsystems are separated from each other by headers. This is done to test each system separately.

In the appendices the whole components list (Appendix A) and the schematics of the PCB design (Appendix B) can be found.

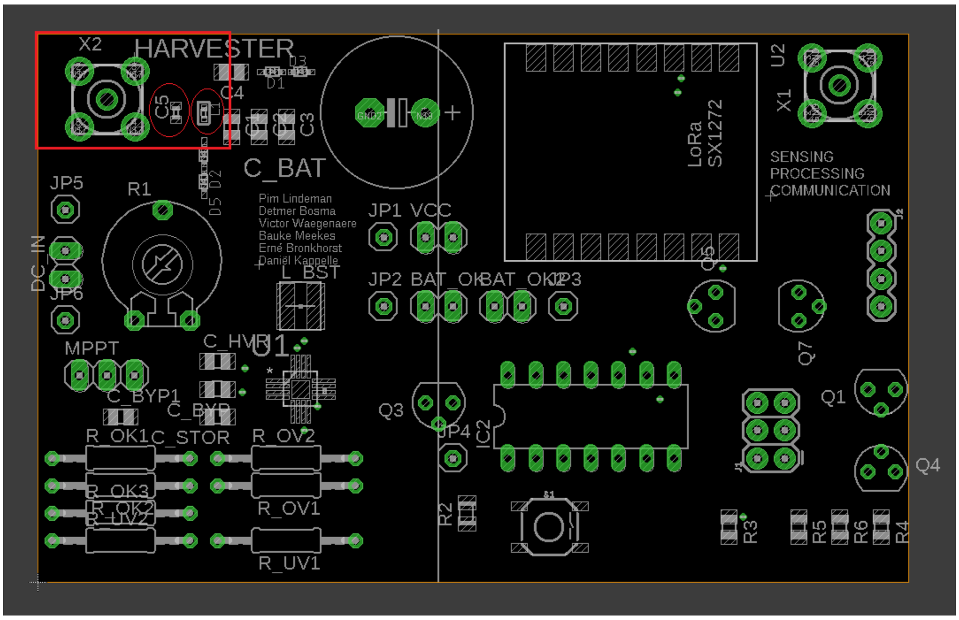

Figure 4.6: PCB of the whole system

4.2.2. Measurements

For testing the matching circuit, the circuit was connected to the VNA at the SMA connector where the antenna is supposed to be connected to. The VNA is used to measure the input impedance of the whole circuit. The results of these measurements with different input power can be seen in Fig. 4.7. The input impedance of the circuit is approximately $Z_{in} = 12.25 + j * 60.60\Omega$. When this is compared to the antenna impedance at 845 MHz ($Z_{ant} = 87.4 - j * 18.45$), it can be seen that they are no complex conjugates of each other whatsoever. This could be due to the fact that it was not possible to measure the actual input impedance of the rectifier circuit without matching circuit as well as that inter-trace capacitances were not considered in the design phase.

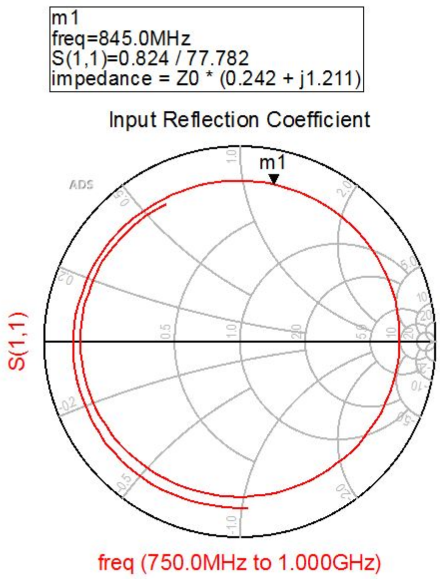

Figure 4.7: Input impedance of the circuit at -25 dBm input power

5
Discussion

A harvesting subsystem is designed, built and tested. Out of these measurements there are some things that stand out and discussed in this chapter.

The measurements of the matching circuit shows the input impedance of the rectifier to be $Z_{in} = 12.25 + j * 60.60\Omega$. This results in a mismatch between the antenna and the rectifier. Due to designing the circuit based on simulations, the actual input impedance of the rectifier may be different. Therefor the transmission of the RF power from the antenna to the rectifier will be less efficient. But even with the lesser connection between the subsystems, the harvested RF power can be converted. The actual input impedance of the rectifier circuit should be measured with a VNA. This should be done by shorting the capacitor in the matching circuit and removing the inductor. This way the SMA connector is directly connected to the rectifier circuit which makes it possible to measure the S-parameters of the rectifier itself.

The measurements of the antenna impedance were done using a SMA connector that was designed for 50Ω antennas/transmission lines. This might have influence of the overall impedance of the antenna. This means the impedance of the actual antenna itself might differ. The problem that occurs when no SMA connector is used is that measurements can not easily be done since one can not simply attach the antenna to the VNA without a connector.

In the measurements of ambient RF power in an office environment, a setup was used as explained in section 3.1. In this setup, an older type of spectrum analyzer was used (HP 8592A, series of 1987) [24]. The results of the measurement were good and reliable. On the other hand the sweep time is noticeably long, which means that during the sweep of the spectrum some peaks will be missed. This makes the measurements less detailed but not less reliable. Also, a measurement of the receiving RMS value for voltage and power would be interesting information for determining how long it would take to charge the capacitor which stores the energy for sending sensor information, and therefor how often it is possible to send a packet to the LoRaWAN network. Unfortunately, no adequate measuring equipment was available to measure these values.

If Fig. 3.13 and Fig. 4.4 are compared to each other, there can be found a difference in the bandwidth. The bandwidth of the antenna decreases when the antenna is matched. This is a consideration that has to be made. Some design changes could be made to increase the bandwidth and compensate the decrease of the matching circuit. A possible change is to place the patch of the antenna at the edge of the ground plane, with the shorting plate at the edge [22].

6
Conclusion

A planar inverted-F antenna was designed and manufactured for harvesting energy in the GSM band at a frequency of 845 MHz. The antenna has compact dimensions of 38x58 mm (LxW). The unmatched antenna has a peak reflection coefficient of -15.4 dB at 860 MHz. The matching circuit of the antenna still needs improvements. The antenna is able to harvest a power of -25 dBm, which is enough for further conversion to be a useful power source.

The entire IoT sensor, including the conversion and storage subsystem [10] and the communication subsystem[23] has been built on a PCB. Some tests have been performed on the total system. It seems that the harvested power is very little when no RF sources are nearby. It does show however, that it is feasible to further develop this technique and achieve a useful sensor. More extensive testing of the entire IoT sensor and improving the harvested power output are also subject for future work.

6.1. Future Work

In the future, the connection between the antenna and PCB needs extra attention. The antenna should be mounted directly onto the PCB. Ideally, the ground plane of the antenna should be the PCB itself such that only the hoovering plate should be attached. This would prevent any unwanted transmission line effects. Getting rid of the SMA connectors as a first step would improve the accuracy of the simulations since the connectors are designed to be 50Ω, which might not perfectly match the antenna nor the rectifying circuit. This induces unwanted reflections, which limits the power transfer.

If the antenna were attached to the PCB directly, the parameters of the matching circuit can be determined much more accurately. This will result in a higher efficiency and reliability of the system.
The matching circuit needs to be determined more accurately by measuring the actual input impedance of the rectifier circuit. Also the capacitance's caused by the traces on the PCB are not considered in the design of the matching circuit.

There can be taken another look into other antenna designs with higher directivity which would give the antenna much higher gain into a specific direction. This would result in a higher receiving power. Only downside to a higher directivity is that it cannot receive signals from all directions. This must be taken into account when placing the module inside buildings. The antenna must then point to active sources of signals.

In the further future it might happen that the telephone usage of the spectrum changes. This means the frequency of where much energy is transmitted changes. This would also mean that the antenna and rectifier circuit needs to be adapted to other frequencies to be able to harvest enough energy.

A

Parts list subsystem

Table A.1: List of all parts used in the whole system

Ordercode	Aantal	Prijs	Subtotaal	Beschrijving
1654645	1	€ 6,50	€ 6,50	SMA adapter
2112448	3	€ 3,09	€ 9,27	SMA connector
2116082	1	€ 0,34	€ 0,34	Inductor 26 nH (matching)
2809739	1	€ 0,05	€ 0,05	Capacitor 0.9 pF (matching)
1753779	4	€ 0,46	€ 1,84	SMS7630 Schottky diode
1227550	1	€ 0,71	€ 0,71	Potentiometer 10M through-hole
2362111	2	€ 0,23	€ 0,46	Capacitor 4u7 0805
2211001	1	€ 0,32	€ 0,32	Capacitor 0.1 uF 0805
1457736	1	€ 0,32	€ 0,32	Capacitor 0.01 uF 0805
1822600	1	€ 0,54	€ 0,54	Capacitor 2.2 mF
1885453	4	€ 0,33	€ 1,32	Capacitor 180 pF 0805
-	3	€ 0,00	€ 0,00	MOSFET transistor, N-channel
9469273	1	€ 0,09	€ 0,09	5M1 res through-hole
9468730	1	€ 0,06	€ 0,06	4M2 res through-hole
9469834	1	€ 0,08	€ 0,08	6M2 res through-hole
9467955	1	€ 0,08	€ 0,08	3M6 res through-hole
9466894	1	€ 0,08	€ 0,08	2M4 res through-hole
9468730	1	€ 0,06	€ 0,06	4M3 res through-hole
9467947	1	€ 0,05	€ 0,05	3M3 res through-hole
1653018	2	€ 0,03	€ 0,06	51k res 0805
2144306	1	€ 5,32	€ 5,32	DC/DC-converter bq25504
1890602	1	€ 1,40	€ 1,40	Inductor 22uH
3801305	1	€ 0,12	€ 0,12	Reset-button
2500100	1	€ 18,64	€ 18,64	LoRa module
-	1	€ 4,27	€ 4,27	Temperature Sensor Breakout - TMP102
1699394	1	€ 0,97	€ 0,97	AtTiny 24A
Totaal			**€ 52,94**	

B

Full PCB-design

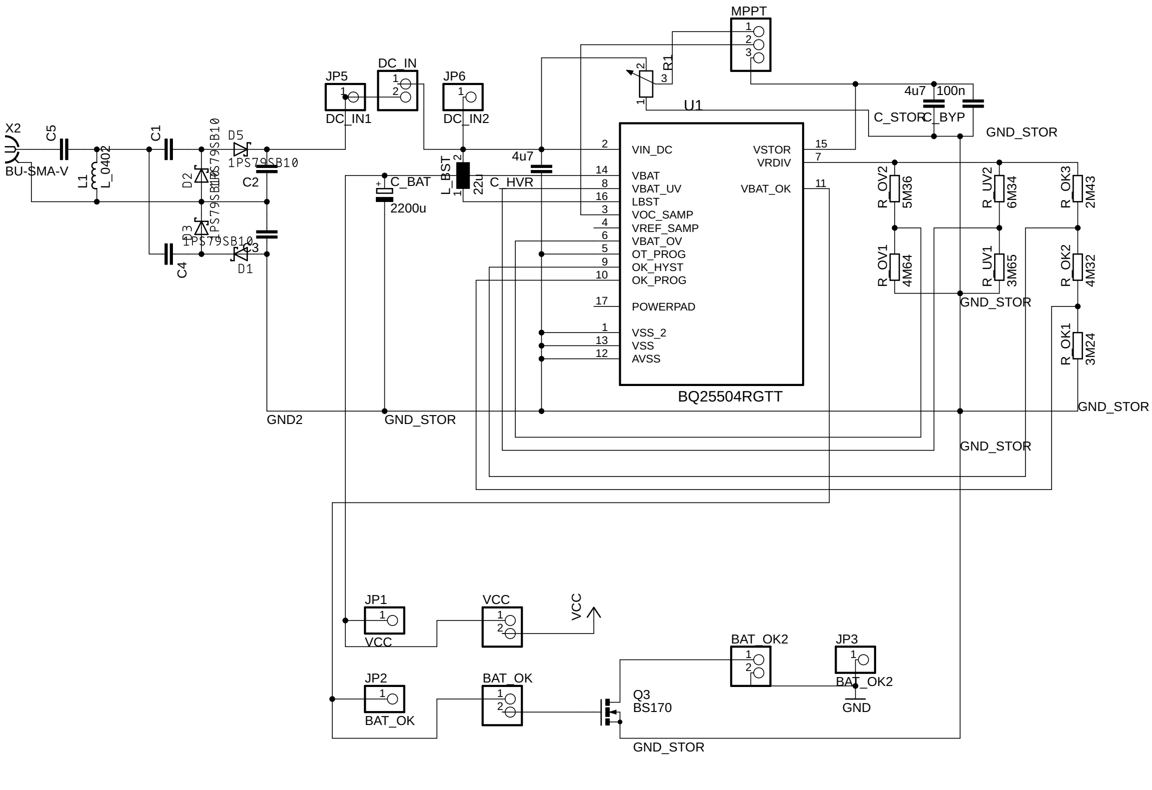

Figure B.1: The PCB design of the antenna and rectifier subsystem

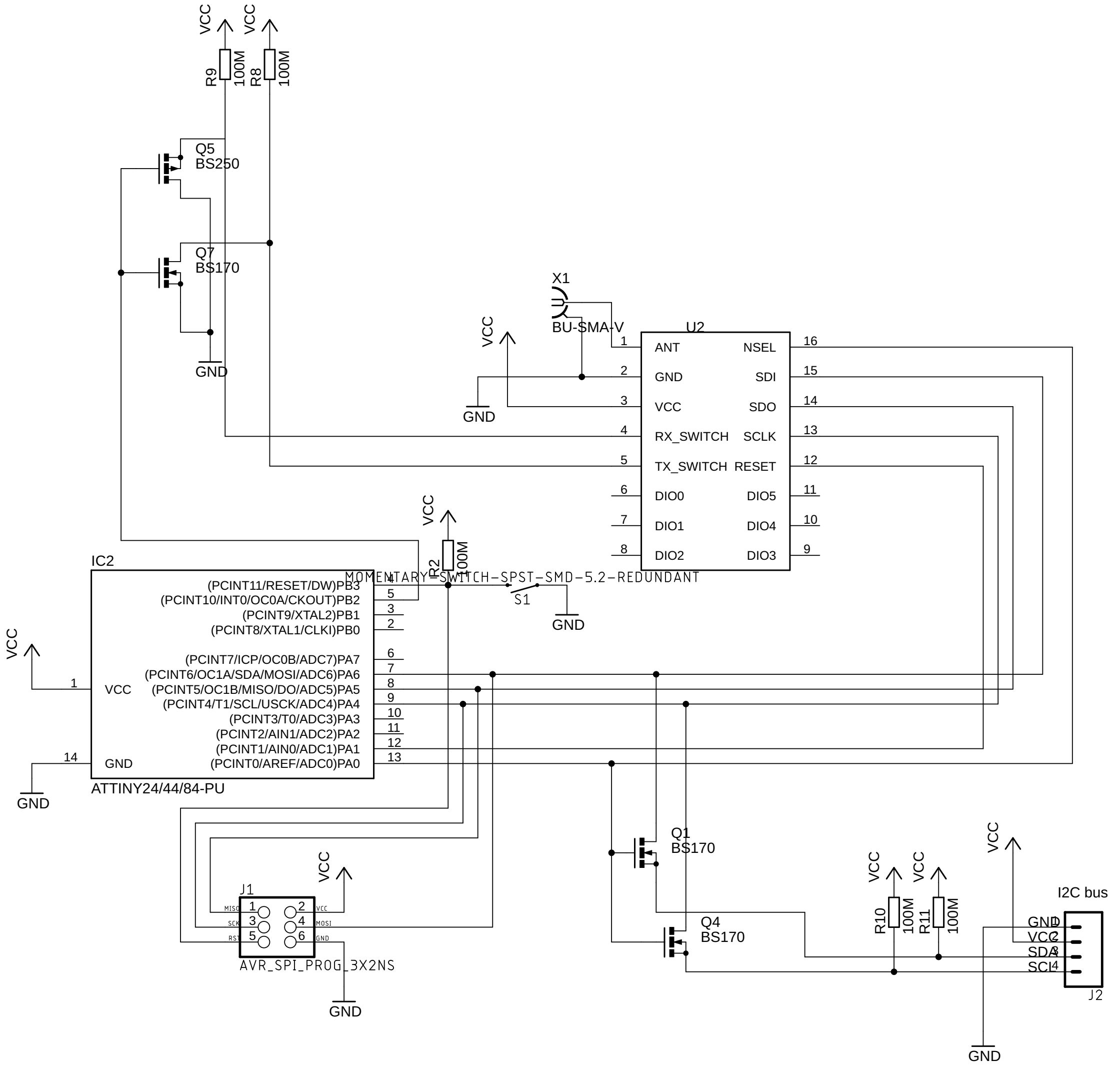

Figure B.2: The PCB design of the sensing and communication subsystem

C
Output voltage rectifier

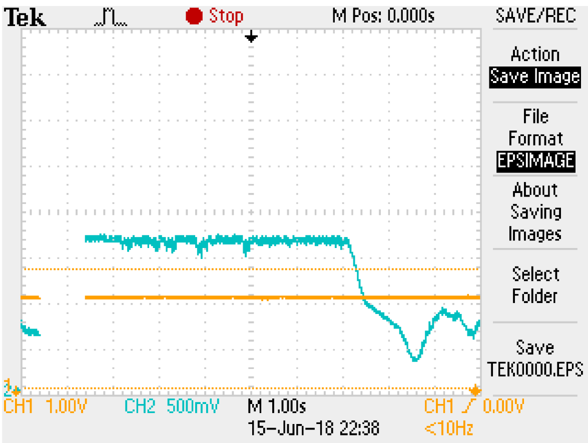

Figure C.1: The output voltage as a phone in close proximity of the antenna was being called. The blue line represents the output of the rectifier, and the yellow line is the output of the DC/DC converter.

Bibliography

[1] T. Sun, X. Xie, and Z. Wang, *Wireless Power Transfer for Medical Microsystems.* Springer Science & Business Media, 2013.

[2] S. Ashley, "Wireless charging: Pulling the plug on electric cars." http://www.bbc.com/future/story/20121120-pulling-the-plug-on-electric-cars, 2014.

[3] N. Tesla, "Experiments with alternate currents of very high frequency and their application to methods of artificiel illumination," *The Inventions, Researches and Writings of Nikola Tesla*, 1891.

[4] NOWI-energy, "Nowi: Enabling the internet of things." https://www.nowi-energy.com/, 2018.

[5] Drayson Technologies LTD. Incorporated, "Freevolt rf energy harvesting - for the low energy internet of things." http://www.getfreevolt.com, 2018.

[6] Powercast Corp., "Powercast - wireless power products." http://www.powercastco.com/, 2018.

[7] D. Snoonian, "Smart buildings," *IEEE Spectrum*, 2003.

[8] Beghelli Canada, "Iec 60529-1 & nema standards." https://www.brenclosures.com.au/wp-content/uploads/BR-Enclosures_IP-Ratings-Chart.pdf, 2003.

[9] International Commission on Non-Ionizing Radiation Protection, "Icnirp guidelines." https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf, 1998.

[10] D. A. Bosma and W. P. Lindeman, "Autonomous battery less sensor for iot applications in smart buildings: Low-power energy conversion and storage for rf energy harvesting," tech. rep., University of Technology Delft, 2018.

[11] Hubrecht J. Visser and Ruud J. M. Vullers, "Rf energy harvesting and transport for wireless sensor network applications: Principles and requirements." https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6495701, 2013.

[12] S. Kitazawa, H. Ban, and K. Kobayashi, "Energy harvesting from ambient rf sources." https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6215815, 2012.

[13] R. Monsano, "Radio frequency energy harvesting and low power data transmission for autonomous wireless sensor nodes." https://repository.tudelft.nl/islandora/object/uuid%3A625d1a77-b39e-417a-9658-122676c47fb5?collection=research, 2016.

[14] V. Talla, B. Kellogg, B. Ransford, S. Naderiparizi, S. Gollakota, and J. R. Smith, "Powering the next billion devices with wi-fi." http://delivery.acm.org/10.1145/2840000/2836089/a4-talla.pdf?ip=145.94.185.111&id=2836089&acc=CHORUS&key=0C390721DC3021FF%2E512956D6C5F075DE%2E4D4702B0C3E38B35%2E6D218144511F3437&__acm__=1529346338_1239abdc6a87a2f775cd12d9157b5f04, 2015.

[15] D. Masotti, A. Costanzo, Massimo Del Prete, and V. Rizzoli, "Genetic-based design of a tetra-band high-efficiency radio-frequency energy harvesting system." https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6679351, 2013.

[16] M. Piñuela, Paul D. Mitcheson, and S. Lucyszyn, "Ambient rf energy harvesting in urban and semi-urban environments." https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6519964&tag=1, 2013.

[17] R. Vyas, H. Nishimoto, D. M. Tentzeris, D. Y. Kawahara, and D. T. Asami, "A battery-less, energy harvesting device for long range scavenging of wireless power from terrestrial tv broadcasts." https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6259708&tag=1, 2012.

[18] U. Muncuk, K. Alemdar, J. D. Sarode, and K. R. Chowdhury, “Multi-band ambient rf energy harvesting circuit design for enabling battery-less sensors and iots.” https://ieeexplore.ieee.org/document/8307395/, 2018.

[19] U. Olgun, C.-C. Chen, and J. L. Volakis, “Mefficient ambient wifi energy harvesting technology and its applications.” https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6349384, 2012.

[20] 4G Masten, “Banden en frequenties.” http://4gmasten.nl/achtergrond/lte-umts-gsm-banden-en-frequenties, 2018.

[21] R. S. Elliott, *Antenna Theory & Design.* Wiley-IEEE Press, 2003.

[22] M.-C. Huynhand W. Stutzman, “Ground plane effects on planar inverted-f antenna (pifa) performance.” https://ieeexplore.ieee.org/document/1232577/, 2003.

[23] E. E. Bronkhorst and D. L. J. Kappelle, “Autonomous battery less sensor for iot applications in smart buildings: Low-power processing & communication,” tech. rep., University of Technology Delft, 2018.

[24] Hewlett Packard, “Hp 8592a portable microwave sprectrum analyzer: Operation manual,” tech. rep., Hewlett Packard, 1987.