Art stocktaking using IoT

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The thesis work carried out in Elektroteknik at Tekniska högskolan at Linköpings universitet

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Abstract

This thesis aims to investigate and propose a solution to realize an artwork stocktaking system. To be more efficient, the system will make use of Internet of Things (IoT) capabilities. Different architectures and communication standards will be analyzed and compared for optimal solution of low power consumption and low cost.

It is shown that the optimal stocktaking system uses two communication standards, i.e., Long Range (LoRa) and Near Field Communication (NFC). LoRa is used to send data from the end node to the server and NFC is used to collect data from a NFC-tag attached to the artwork.

Moreover, the system is designed to be independent from any external power sources i.e., it produces its own power supply. This is done using an energy harvesting system using a photovoltaic cell.

Further hardware design includes two microstrip antennas. The Inverted-F antenna (IFA) and the square-loop antenna were designed and simulated. The IFA is intended for LoRa communication between the end node and the gateway. The square-loop antenna is used to read information on the NFC-tag.

Software was developed to be able to establish communication with a server through the gateway. The Things Network (TTN) was chosen to host the server and visualise the results together with The Things Indoor gateway (TTIG), for good and simple setup.

Finally, theoretical calculations were made to determine how often transmissions could be made assuming that there are eight hours of light a day. The result have shown that a transmission could be made once a day with a low light intensity of only 50 LUX.
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I wish you all the best of luck in the future and I wish that hopefully we will meet each other again.

That’s all folks!

Abbreviations

- LoRa - Long Range
- WiFi - Wireless Fidelity
- PCB - Printed Circuit Board
- GUI - Graphical User Interface
- IoT - Internet of Things
- NFC - Near-Field Communication
- MCU - Micro Controller Unit
- BLE - Bluetooth Low Energy
- LoRaWAN - Long Range Wide Area Network
- CHIRP - Compressed High Intensity Radar Pulse
- CSS - Compressed High Intensity Radar Pulse Spread Spectrum
- MAC - Media Access Control
- LPWAN - Low-Powered Wide Area Network
- ISM - Industrial, Scientific, and Medical
- CRC - Cyclic Redundancy Check
- OTAA - Over-The-Air Activation
- ABP - Activation By Personalization
- RFID - Radio Frequency IDentification
- FNBW - First Null Beam Width
- IFA - Inverted-F Antenna
- PCD - Proximity Coupling Device
- PICC - Proximity Integrated Circuit Card
- IC - Integrated Circuit
- SPI - Serial Peripheral Interface
- I2C - Inter-Integrated Circuit
- UART - Universal asynchronous receiver-transmitter
• MISO - Master In Slave Out
• MOSI - Master Out Slave In
• SCK - Serial Clock
• SS - Slave Select
• LDO - Low-Dropout
• LVOUT - Low Voltage Output
• HVOUT - High Voltage Output
• SoC - System on Chip
• ADS - Advanced Design System
• EMC - Electromagnetic Compatibility
• TTS - The Things Stack
• TTN - The Things Network
• TTIG - The Things Indoor Gateway
• BOM - Bill Of Materials
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1 Introduction

In this chapter, the master thesis will be introduced. The motivation and aim are shortly presented. Then, the research questions are listed as well as delimitations.

1.1 Motivation

Today, in public buildings such as museums, hospitals, universities, etc., there are a lot of historical and modern works of art. To make periodical inventory or to be sure that they are on their correct location is a challenge as process and in terms of time and costs. Tracking objects and keeping them safely usually implies cameras and motion detectors. But this is not the case for all the art objects spread in a multitude of buildings other than museums. In Sweden, more specifically Region Ostergotland, employees have to scout for these artworks every other year. Because of this situation, Region Ostergotland has initiated a collaboration with RISE research institute aiming the design of an artwork stocktaking system.

Region Ostergotland is leading the regional development in the region. They have several responsibilities such as people’s health, culture and entrepreneurship, [17]. On several of these locations such as museums and hospitals there are artworks that the region owns. RISE is an independent research institute owned by the state, that cooperates with companies, academy and public sector to contribute to a competition-heavy business and a sustainable society, [20].
1. **Introduction**

1.2 **Aim**

The aim of this thesis work is to investigate the possibility of, propose a solution and design an automated system that handles the art stocktaking. The main idea is that every artwork will be aided with a device to be able then to send messages to a database that employees have access to. The database gets information about the artwork whereabouts and can conclude if the artwork is on the right place, or if the artwork is missing. Every artwork has an ID that the database recognizes. If an artwork is moved a new location, the employees then can change the ID of the artwork in the database. A requirement from Region Östergotland is the cost of the final module, i.e., every module should cost around 100 Swedish crowns per artwork and for production of 20,000 modules.

1.3 **Research questions**

During the thesis work several questions will be answered. These questions are listed as follows:

1. Which architecture is most appropriate for the installation environment?
2. Which type of communication is most appropriate for this application? Some examples to be investigated are LoRa, Cellular, WiFi or Ethernet.
3. How often can messages be sent if the system charges eight hours/day?

1.4 **Delimitations**

There are some delimitations that need to be considered during the thesis work. One delimitation is that the system will only be used in an indoor environment where the lights are on at least 8 hours per day. The system will also only be used for paintings and not sculptures. The information that the system is sending does not have to be compatible with Region Östergotland’s databases. This means that an interface which contains the ID of the artworks and the position is enough. Being a low-power application, it is assumed that solar cells and batteries will be used in the project. Epishine and Ligna Energy are the first hand choices.

1.5 **Project approach**

The project will be initiated with the project planning. This planning will include a time diagram, so that the time needed for different steps of the project work will be estimated and the progression of the project will be accordingly followed. In parallel, a literature study will be performed to analyse different architectures that might be used in this project. At the beginning at the project, two different architectures were discussed with the company. These architectures will be examined and compared. Then, other possible options will be considered. Also, the components from Epishine and Ligna Energy will be examined to make sure that they can be used in the project and get the desired result. Power consumption will be estimated theoretically and practically early in the project. This is done by examining if the solar cells can power the different components to maintain enough energy to send messages to the database. Finally, different types of communication requires different amount of energy, thus different communication methods will be investigated such as WiFi, LoRa and Bluetooth.

After the architecture and type of communication have been established, design of the hardware and the software will performed. Hardware design implies that after choosing different components and understanding how they communicate, a PCB will be designed. To implement the wireless system, two antennas will be designed for the communication
between the gateway and the reader, and between the reader and the tag. Parallel with the hardware design, the software development will be done. The software is divided into three major parts, these are “System”, “Communication” and “GUI”. The “System” handles the hardware and reads the information about the artworks whereabouts. The “Communication” takes care of the communication between the hardware and the gateway, this information is then shown on a “GUI”, which shows the artworks ID and the positions ID.

It is also desirable that the system or parts of the system will be tested in a real environment to evaluate its operation. This is done if the system is done before the end date of the project and there is time remaining for the test. In the case of an existing prototype, the demonstration will take place at a location provided by Region Östergötland.

1.6 Planned literature base

Literature that will be used under the project work are scientific papers about different appropriate architectures that will eventually be used. Scientific papers will also be used to research about how IoT system works and how IoT technology can be used in this project. Data sheets with specifications about solar cells and other components will also be studied.
In this chapter, theoretical aspects used to answer the research questions and investigation of the parts included in this project will be presented.

2.1 Stocktaking and IoT

In general, stocktaking is the process of recording the amount of stock a company has. The stock can be everything the company owns from food to monitors and other products e.g., in this work, artworks. Stocktaking is important to understand the value you posses and makes sure that the things owned by the company do not disappear or gets lost. Unfortunately, stocktaking is a tedious process and often takes a lot of important work time from the company where more productive things could be achieved. This is were Internet of Things (IoT) is a solution, [9].

IoT is a collective name for devices with built-in electronics and a wireless connection. Sensors are commonly used with IoT devices to relay information such as temperature, distance, or luminosity to the end user. IoT is used in many different areas such as automotive, industrial and personal use, usually to make work easier and more efficient. The low-cost solutions are integrated with many modern products to make them “smart” by enabling wireless communication and control through an accessible wireless network. Different types of wireless networks are used for these applications and will be investigated later in the thesis, [9].

The combination between IoT and stocktaking creates a good “smart” solution for stocktaking. It reduces the time wasted and with that reducing the overall cost of operation for a company, whilst removing the tedious part of stocktaking.

2.2 Proposed stocktaking system architectures

As mentioned in Chapter 1, two different architectures have been discussed from the beginning of this project to find the optimal solution given the resources and information that Region Ostergotland has provided.
The system in Figure 2.1 consists of a single unit that communicates with the gateway. In Figure 2.2, there are two devices for each artwork to communicate with the gateway. The two different architectures have their advantages and disadvantages. Architecture 1 uses tracking methods to determine the painting location. The travel time and the angle to approach the painting location should be calculated. Architecture 2, is a simpler method that uses a device both on the wall as well as the painting to determine that the painting is hanging at the right location. This is done using for example an Near Field Communication (NFC) tag on the painting and a NFC-reader on the wall. The reader scans the painting and send the obtained data to the server. The data being sent is a combination of both ID of wall and ID of painting.

Figure 2.1: Architecture 1

Figure 2.2: Architecture 2
2.3 Communication standards

In Figure 2.3, the block diagram of the proposed system is shown. One of Region Oster-gotland’s request was that the system should be independent from an external power source, this is why an energy harvesting system must be implemented into the system. The system is also thought so that the module can differentiate among different locations and different paintings. This is done using the data collection block. The MCU controls the entire systems by sampling data and then transferring this data to the gateway. The data is then displayed at the server and can then be modified to create a good visual representation of where different paintings are hanging.

![Figure 2.3: System overview](image)

2.3 Communication standards

In this section, different possible communication methods for relaying information from the end node to the gateway will be presented. Questions to be asked are, where will the system be implemented? How far apart will the devices be from the object to be identified? How does the architecture of the building/room look like?

The artworks are installed in many different places such as hospitals, museums and other public places. Whilst a museum might have many painting concentrated in smaller areas, a hospital might only have one painting in a hallway. This means that the solution must be flexible and adaptable to different environments.

The communication must be done with low power consumption. Solarcells and super-capacitor are proposed to be used. Generally, IoT applications are thought from the beginning to be of low power type.

The communication methods that were analyzed are presented as follows:

Bluetooth Low Energy

Bluetooth Low Energy (BLE) was introduced in 2010. It uses the unlicensed 2.4 GHz ISM (Industrial, Scientific, and Medical) band to communicate. BLE is defined as a short-range, low-power communication standard dedicated to low power applications. BLE is also a very flexible communication method that allows the developer to adapt the communication to a specific application. E.g., the developer can choose a point to point connection or a mesh type connection, [27].
BLE protocol

The BLE protocol is a stack structure built up of three main blocks, as shown in Figure 2.4. The controller block consists of two parts, the link layer (LL) and the physical layer (PHY). The block defines the communication parameters such as frequency value and modulation type. The data get transferred to the host through the Host controller interface (HCL) that manages the communication between the hardware and the user application. The Host block consists of security manager protocol (SMP), Attribute protocol (ATT), Logical link control and adaptation protocol (L2CAP), Generic attribute profile (GATT), and Generic access profile (GAP). The data get transferred to the highest block Application (APP) that represents the direct interface with the user. The L2CAP part has two functions serving both as a protocol multiplexer and fragmentation and recombination. This function is necessary to form the standard Bluetooth packets. The L2CAP is responsible for controlling both the ATT part that handles the data exchange to and from the application and the SMP part. This is responsible for the security keys between the parts. GATT and GAP are responsible for the connection between the peers, where GAP is for the used topology and GATT is for communication attributes, [26], [27]. The Protocol stack is visualized in Figure 2.4.

LoRa/LoRaWAN

LoRa stands for long range and is a low-frequency radio communication standard based on spread spectrum modulation. The spread spectrum modulation is Compressed High Intensity Radar Pulse (CHIRP) spread spectrum (CSS). Equivalent to BLE, LoRa is of low power characteristics, which makes it a commonly used communication method for IoT applications.

LoRa is the physical layer and LoRaWAN is the Media Access Control (MAC). Together, they create a low-power Wide Area Network (LPWAN). LPWAN is a wireless IoT communication standard with large coverage areas, slow transmission rates, and low power consumption ideal for IoT use. The communication operates in the sub-GHz ISM band between 433 MHz and 915 MHz, depending on geographical location. Europe uses the frequency of 868 MHz, [11]. The end nodes are communication to and network server through a gateway, the network server handles the information obtained from the end nodes and relays this information to an application. This is illustrated in Figure 2.5, [25].
CSS in LoRa

CSS is a communication spread spectrum technique that uses chirp signals, modulated by the data (information) to be transmitted. The chirps are linear frequency modulated (LFM) signals, with frequency sweeping between 125 kHz and 500 kHz in the case of LoRaWAN. The sweep speed of the chirp signal dictates the data transmission rate: lower spreading factors mean faster chirps and with that, higher data rates. In chirps, the frequency can change from lower frequency values to higher frequency values, see Figure 2.6. This is called up-chirp. Chirps of opposite frequency variation, from higher to lower frequency values are called down-chirps.

The communication between the end node and the gateway consists of four parts: the preamble, sync, payload and cyclic redundancy check (CRC). The preamble is used to inform the gateway that a payload is about to be received. This is followed by the sync part that
consists of two down-chirp signals. The following part is the payload being sent. This is done using discrete frequency steps. Each block carries 8 bits. The last block is the CRC. It is responsible to confirm that all the bits were received correctly, [15].

Security

To encrypt the communication between the parts, a 128-bit Advanced Encryption standard (AES-128) is used. When a device connects to the network, two keys are generated, the 128-bit application session key (AppSKey) and the 128-bit network session key (NwKSKey). The NwKSKey is shared with the network and is therefore a public key, while the AppSKey is kept private. The NwKSKey is responsible for the interaction between the node and the server. The key is used to validate each message being sent between the two parts and makes sure that no intentional interference has been made. The AppSKey is used to encrypt the Payload between the node and the application server, [13]. The session keys are assigned to the end device during the activation, in LoRa there is two types of activation, Activation By Personalization (ABP) and Over-The-Air Activation (OTAA). ABP has hard-coded session keys that are pre-selected, this give the node a opportunity to skip the join procedure making the communication more energy efficient. OTAA generate dynamic session keys each time the node enters the join procedure, this makes the communication more secure between the devices and gives the system more freedom for changes in the system, [14].

Other wireless communication standards

Beside LoRa, there are some other classical or newer, wireless communication standards that can be used in IoT applications. Among them, WiFi and cellular but also ZigBee and SigFox.

SigFox is a low-power, wireless standard similar to LoRa. It also operates in the sub-GHz frequency range. In Europe it operates at the frequency of 868 MHz, just like LoRa. SigFox has a more narrow bandwidth of only 100 MHz compared to LoRa that can have a bandwidth of 125 MHz to 250 MHz, depending on the configuration. SigFox is similar to a cellular network in where an existing network already exists and is operated from the company itself rather than the user setting up a network them self. In this project, this would be hard to setup since there is no coverage at the locations the device would be worked on and setup, [8].

ZigBee is similar to BLE. It communicates within the same 2.4 GHz ISM band. BLE is more configurable than Zigbee and gives the developer the ability to customise the communication to the given specification, [19].

Wireless Fidelity (WiFi) is a Wireless Local Area Network (WLAN). WiFi has longer range than BLE but shorter than LoRa. It is a good method for IoT application due to the accessibility of WiFi in both homes and commercial-places. However, WiFi is the worst communication standard when considering power consumption, therefore only good for applications using wired power sources, [18].

Near Field Communication

NFC stands for "Near Field Communication" referring to a short-range, high frequency, low bandwidth, wireless communication that takes place between two NFC devices. The frequency of operation for NFC devices is 13.56 MHz, which was originally used by Radio Frequency Identification (RFID). NFC enables communication between a NFC reader and a passive NFC tag on the other end. Some examples of applications where NFC is used are e-payment, e-ticketing, identification, money transfer, social services and so on. NFC operates between two devices over a very short communication range. NFC operates in different operating modes, these being: reader/writer, peer-to-peer and card emulation. The reader/writer mode enables one NFC device to exchange data with another NFC tag. The peer-to-peer
mode enables two NFC devices to exchange data with each other. The card emulation mode, a mobile phone can be simulated as a smart card to communicate with an NFC reader. The NFC tag can either be active or passive, active meaning that the tag is supplied by a power source, and passive means that the tag is not powered. This means that the passive tag is supplied by the induced current from the NFC antenna, and is completely off when communication is not on. In this project, the reader/writer mode will be used, [5].

The main motivation for using NFC, is the possibility of integration of personal and private information, such as credit card information och mobile phone data. These approach however can conduct to security aspects being of concern. RFID is considered to have too long range for security reasons, [5].

2.4 Antennas

In this section, elements of antenna theory will be presented as antennas are required in this project. Two types of antennas will be designed using a dedicated design software. At first, radiation will be discussed to understand how an antenna operates. Then, different types of antennas and antenna parameters will be presented.

How does radiation occur?

One question that should be answered before cover what an antenna is, is how is radiation accomplished, meaning how are the electromagnetic fields generated? One example to look at is how radiation occurs in a single wire. Through a conducting wire, the motion of electric charges creates what is called a current. It is assumed that the electric charge volume density $q_v$ is evenly distributed in a wire with cross-sectional area $A$ and volume $V$. Also, that the total charge $Q$ in volume $V$ is moving in the $z$-direction with a velocity $v_z$, [3] as represented in Figure 2.7. This generates a current density $J_z$ in the wire. The equation for the current density can be written as:

$$J_z = q_v v_z$$  \hspace{1cm} (2.1)
In a very thin wire with $r \approx 0$, the current can be represented by

$$I_z = q_l v_z \quad (2.2)$$

If the current is time varying, from Equation 2.2 the variation in time of the current can be written as:

$$\frac{dI_z}{dt} = q_l \frac{dv_z}{dt} = q_l a_z \quad (2.3)$$

where $a_z$ is the acceleration in z-direction (m/sec$^2$). With the length $l$, Equation 2.3 can be written as:

$$l \frac{dI_z}{dt} = l q_l \frac{dv_z}{dt} = l q_l a_z \quad (2.4)$$

Equation (2.4) shows the relation between the electrical current and charge. It states that a time-varying current or an acceleration or deceleration charge is needed to create radiation. To achieve acceleration or deceleration of a charge, the wire must be curved or bent, [3]. Therefore:

- If a charge is stationary, coulomb field is present but no radiation.
- If a charge has a constant velocity in a straight wire, a magnetic field is present but no radiation.
- If a charge has a constant velocity in a curved or bent wire, radiation occurs.
- If a charge is oscillating in a time-motion, radiation occurs even in a straight wire.

What is an antenna?

Antennas are devices that enable wireless communication being the interface between the hardware and the free-space medium through which the electromagnetic waves propagate. In other words, the antenna is the transitional structure between free-space and a guiding device. The guiding device or transmission line can be e.g., a coaxial cable, and it is used to transport electromagnetic energy from the source to the antenna for a transmitting antenna. Once the signal is sent, a receiver antenna will get and guide it to the following receiver hardware. There are several types of antennas, some examples are, wire antennas, aperture antennas, microstrip antennas, array antennas and reflector antennas. These types of antennas can have different antenna parameters. The type of antenna that is chosen is thus related to the application, [3].

![Figure 2.8: Patch antenna, [3]](image-url)
Figure 2.8 shows an example of a microstrip antenna. The antenna is a patch antenna placed on a PCB having a bottom ground plane. This results in the radiation occurring orthogonal to the antenna plane. Microstrip antennas are becoming increasingly useful because of manufacturing aspects. The microstrip antennas can be integrated directly on the circuit board, are easily fabricated, have a low cost and are small in size. With these pros, they are the best solution to be integrated with the rest of the hardware system. They are also mechanically robust and are generally very versatile in terms of resonant frequency and impedance. In this project, two different microstrip antennas were designed, Inverted-F antenna and square-loop antenna.

Antenna parameters

Antenna parameters indicate how the antenna behaves. These parameters are considered when choosing an antenna depending on the application and when the antenna is designed. Usual antenna parameters are, radiation pattern, bandwidth, directivity, gain and efficiency.

- Radiation pattern is a visual representation of the radiation properties of the antenna as a function of space coordinates. This means that radiation pattern shows how much and in what directions the antenna will radiate. Some properties that can be represented are radiation intensity, field strength, directivity, phase and polarization. The field patterns are often normalized to give a maximum power of 1, this simplifies other properties that can be explored, [3].

![Field Pattern](image)

Figure 2.9: Field pattern, [3]

Figure 2.9 shows an example of what radiation pattern for an antenna looks like. The big lobe is referred as the main lobe and the smaller ones are referred as minor lobes. In the figure, HPBW can also be seen, which stands for "Half Power Beam Width". HPBW is a measurement on the main lobe where the antenna radiates half power or more.
Figure 2.10: HPBW and FNBW, [3]

Figure 2.10 is another representation of radiation pattern. In this figure, half power beam width can be seen and FNBW as well. FNBW stands for "First Null Beam Width" and is the width of the whole main lobe, in other words FNBW is the angular separation between the first nulls.

- Bandwidth is considered to be the range of frequencies, on either side of the center frequency, where the antenna parameters are within an acceptable value of those of the center frequency. The bandwidth does not have a specific characterization because the parameters or the characteristics of an antenna does not necessarily vary or being affected by the frequency. The factor that affects the bandwidth the most is the impedance of the antenna, therefore it is important that the antenna is matched properly. Mismatch causes the antenna to resonate at a different frequency other than the desired frequency, and causes the bandwidth to be narrow. If the bandwidth is wide, there is more room for error when matching the antenna, [3].

- Directivity of an antenna is referred as the ratio of the radiation intensity in one given direction from the antenna to the radiation intensity averaged over all directions. This means that higher directivity values correspond to a more "directional" antenna, [3]. The mathematical definition of the
directivity is shown in (2.5):

\[
D = \frac{4\pi U}{P_{rad}}
\]  

(2.5)

If the direction is not specified, the directivity is then expressed as:

\[
D_{max} = \frac{4\pi U_{max}}{P_{rad}}
\]  

(2.6)

where

- \(D\) = directivity (dimensionless)
- \(D_0\) = maximum directivity (dimensionless)
- \(U\) = radiation intensity (W/unit solid angle)
- \(U_{max}\) = maximum radiation intensity (W/unit solid angle)
- \(P_{rad}\) = total radiated power (W)
For antennas with orthogonal polarization components, the partial directivity is that part of radiation intensity corresponding to a given polarization divided by the total radiation intensity average in all directions, [3]. For spherical coordinates, the maximum directivity with the orthogonal components $\theta$ and $\phi$ can be written as:

$$D_\theta = D_{\theta} + D_{\phi}$$  \hspace{1cm} (2.7)

$$D_{\theta} = \frac{4\pi U_{\theta}}{(P_{rad})_{\theta} + (P_{rad})_{\phi}}$$  \hspace{1cm} (2.8)

$$D_{\phi} = \frac{4\pi U_{\phi}}{(P_{rad})_{\theta} + (P_{rad})_{\phi}}$$  \hspace{1cm} (2.9)

where

$U_{\theta}$ = radiation intensity in a direction given by the $\theta$ component
$U_{\phi}$ = radiation intensity in a direction given by the $\phi$ component
$(P_{rad})_{\theta}$ = radiated power in a direction given by the $\theta$ component
$(P_{rad})_{\phi}$ = radiated power in a direction given by the $\phi$ component

For a half-wavelength dipole antenna, i.e., $l = (\frac{\lambda}{2})$, the directivity can be approximated by:

$$D = D_\theta sin^3 \theta = 1.67 sin^3 \theta$$  \hspace{1cm} (2.10)

Figure 2.11 shows the two-dimensional and in three-dimensional directivity patterns for the half-wavelength dipole antenna. It can be seen in (a) that the dipole has the maximum directivity at $\theta = \pm 90^\circ$ and its value is 1.67. The directional patterns can also be visualized in three dimension, this is seen in (b). In this case, the directivity is dependent on $\theta$ and $\phi$. Since $\phi$ revolves around the z-axis, the directivity as a function of $\phi$ will always be 1.67 in this case.
Antenna efficiency is how effective an antenna is to transfer the power from a transmission line to free space and vice versa. The total antenna efficiency $e_0$ is taking into account losses. Losses can be reflections due to mismatch at the antenna input and also conduction and dielectric losses, [3]. Total antenna efficiency can be written as

$$e_0 = e_r e_c e_d$$

Where

- $e_0$ = total efficiency (dimensionless)
- $e_r$ = reflection efficiency = $(1 - |\Gamma|^2)$ (dimensionless)
- $e_c$ = conduction efficiency (dimensionless)
- $e_d$ = dielectric efficiency (dimensionless)
- $\Gamma$ = voltage reflection coefficient. This determines how much of the voltage that is reflected back to the source. $\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$

Gain is an useful parameter to consider when describing an antennas performance. The gain is closely related to directivity. It takes into account the efficiency of the antenna and its directional properties as well. The gain of an antenna is the ratio of intensity in a direction to the radiation intensity what would be obtained if the power delivered to the antenna would be radiated isotropically, [3]. This can be written as:
2.4. Antennas

\[ G = 4\pi \frac{U(\theta, \phi)}{P_{in}} \text{ (dimensionless)} \]  

(2.12)

Most of the time when measuring gain, relative gain is measured. Relative gain is basically the gain of a given antenna compared to another antenna, usually a dipole antenna. The reference antenna is in most cases a lossless isotropic source. Thus, in (2.12), the denominator would be \( P_{in} \), (lossless isotropic source). Note, when the direction is not stated, the power gain refers usually to the power gain in the direction of maximum power.

Total radiated power is related to the input power and can be written as:

\[ P_{rad} = e_{cd} P_{in} \]  

(2.13)

Where \( e_{cd} = e_c e_d \) = antenna radiation efficiency. The gain does not include losses from mismatches.

Using (2.12) and 2.13 results in:

\[ G(\theta, \phi) = e_{cd} \left[ 4\pi \frac{U(\theta, \phi)}{P_{rad}} \right] \]  

(2.14)

Since gain is related to directivity, (2.5) can be used to get:

\[ G(\theta, \phi) = e_{cd} D(\theta, \phi) \]  

(2.15)

Similarly to directivity, maximum gain for the orthogonal components can be written as

\[ G_0 = G_{\theta} + G_{\phi} \]  

(2.16)

and the partial gains can be written as

\[ G_{\theta} = \frac{4\pi U_{\theta}}{P_{in}} \]  

(2.17)

\[ G_{\phi} = \frac{4\pi U_{\phi}}{P_{in}} \]  

(2.18)

where

\[ P_{in} = \text{total input power (W)} \]

Field regions

The space surrounding the antenna is divided into three regions. These are, a) the reactive near-field, b) radiating near-field and c) the far-field. The Reactive near-field region is the region that is closest to the antenna. In this region magnetic and electric reactive fields are dominant fields. These fields are usually non-predictable and they are not used in classical antenna applications where the radiation is assumed to propagate. The Radiating near-field region, is the region between the reactive near-field and the far-field. In this region, the angular field distribution are dependent on the distance from the antenna. If the antenna has a maximum dimension that is not large compared to the wavelength, this region may not exist. For an antenna focused at infinity, the radiating near-field is sometimes referred to as the Frensel region. If the antenna has a maximum dimension very small compared to the wavelength,
this region may not exist. The *Far-field region*, also called the Fraunhofer region, is the region where the angular field distribution is independent of the distance from the antenna [3].

Figure 2.12 shows the field regions of an antenna, where

- \( D \) = antenna maximum dimension
- \( \lambda \) = wavelength
- \( R \) = distance

![Antenna field regions diagram](image)

**Figure 2.12: Antenna field regions, [3]**

Figure 2.13 shows how the amplitude patterns change when moving through these three regions. It can be seen that in the reactive near-field the pattern is more spread and uniform, so no main or minor lobe can be observed. In the Radiating near-field region, lobes are starting to form and the pattern is more smooth. In the far-field region, the pattern is well formed and the major lobe is apparent with one or several minor lobes. Therefore when simulating and using theoretical equations, the radiation patterns are in the far-field. If the observer point is in the near-field region, the result will not be the same as theory.
2.4. Antennas

Figure 2.13: Amplitude pattern change from reactive near field toward the far field, [3]

**Microstrip Inverted-F Antenna**

The inverted-F antenna is a popular microstrip antenna due to its compact design, good impedance bandwidth and for its flexibility when integrated with other circuits on the same PCB. It is used in many applications such as Bluetooth, Zigbee and other applications. In its operation, the antenna is highly dependent on the ground plane and its size. These are the main specification resulting from the design process. The antenna is also sensitive to nearby metal, due to the fringing fields of the antenna that might not couple to the ground plane, but to the nearby metal surfaces, other than grounded.

An example of an Inverted-F antenna layout is shown in Figure 2.14. It can be seen that the inverted-F antenna originates from a monopole antenna that is bent into an L-shape, where the shorting pin is connected to ground and the antenna is fed in the proximity of the shorting pin.
As indicated in Figure 2.14, the inverted-F antenna is implemented in such a way that the antenna is placed outside the ground-plane. Then, the shorting pin connects the antenna to the ground-plane. The antenna feeding point is the point where the driving signal is applied to the antenna. The connector is also connected to the ground plane. A common implementation technique is shown in Figure 2.15.

The inverted-F antenna alone can be broken into two major parts: the shorting pin and the open arm. The open arm is located to the right of the feeding point and has capacitive behaviour due to the open end. The shorting pin is connected to ground which means that it has inductive behavior. This means that if the shorting pin and the open arm have the same electrical length, the inductance and capacitance will cancel each other at a certain frequency and the antenna equivalent circuit will a resistor. This means that the antenna will act like an LC-resonator. An equivalent circuit model is shown in Figure 2.16. The inductance is equivalent to the shorting pin and the capacitance is equivalent to the open end. The resistance represents radiation resistance, which causes losses in power when radiation occurs.
2.4. Antennas

Figure 2.16: Inverted-F antenna circuit model, [10].

Microstrip square-loop antenna

The square-loop antenna is a type of near-field communication (NFC) antenna. As mentioned in Section 2.3, NFC is just a method of communication between two devices at short distances. In this project, the NFC is specified to operate at the frequency of 13.56 MHz. The corresponding wavelength is then $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{13.56 \times 10^6} = 22.12$ m. This means that, e.g., if it should be implemented as a half-wavelength dipole, the antenna would be 11 m long. In reality, NFC antennas are not real antennas; radiation pattern or gain does not matter. They use instead the near-field region for operation, where the fields do not propagate. [2]. This is why, typical NFC antennas are particularly small antennas where no radiation will occur. This is why classical antenna parameters do not mean anything for the design evaluation, e.g., the antenna efficiency will basically be nonexistent.

The mechanism behind an NFC antenna is based on the fact that an inductor can couple with another inductor causing mutual coupling. This means that, if the magnetic field from one inductor pass through another, a current will be induced in the second inductor. This is the contactless energy transfer that NFC requires.

The NFC antenna is simply a large value inductor, while the term "antenna" is used as it is convenient for the near-field operation description. The larger the inductance, the better the antenna will perform. In its implementation, the NFC antenna is simply a metal wire looped with several turns, the more turns, the larger inductance, [2]. An example of this is shown in Figure 2.18. The PCD Antenna Coil is the NFC antenna and the PICC Antenna Coil is the passive tag antenna. The image to the right in Figure 2.18 is an equivalent circuit diagram of the communication between two NFC devices.

In Figure 2.17, the NFC reader excites a current at the frequency 13.56 MHz at the reader antenna. The current induces a magnetic field, which then couples with the second NFC antenna. Since the antenna is really and inductor, the main specification is the inductance of the antenna. One rule of thumb to consider when designing an NFC antenna is that the antenna should have an inductance of at least 1$\mu$H. Higher value inductance can be implemented and this is controlled by the amount of turns of the antenna, [2].
2.5 Energy harvesting

In this master thesis work, the system is specified to be independent from any external power sources. Therefore, the system should be able to collect from the environment energy, then generate and store this energy by itself. This process is in fact known as Energy Harvesting. Energy harvesting is often used for autonomous and battery-less systems, often specified for low-power consumption.

In this project, three solutions are needed: 1) the way to capture the energy, 2) a way to store the energy and, 3) a management system that manages the energy between the two.

There are multiple methods to capture energy from the ambient environment e.g., vibration/motion energy, thermal energy, light or RF radiation. Photovoltaic harvesting uses photons from light to harvest energy by using a solar cells. The solar cell converts the incoming photons into electricity to be used as power for the electronics in the system, [28].

The energy captured by the device needs to be stored somewhere, this is where a energy storage device is used. Different types of energy storage can be used for energy harvesting, e.g., batteries, super capacitors and normal capacitors. These are meant to power the device
2.6. MicroController Unit

For this project to be efficiently implemented, a power management system is needed. The power manager is responsible for making sure that the voltage and current generated from the harvester can be fed into the storage unit and when the storage capacity is full, redirect this power. Moreover, power management systems are often equipped with output voltage regulators, used to feed the required voltage to the systems, [6]. To conclude, energy harvesters are an optimal solution as they enable autonomous and environment friendly systems. To be optimal, the for li

2.6 MicroController Unit

To control all the communication and peripherals, a MicroController Unit (MCU) is needed. A MCU is a small computer on an Integrated Circuit (IC) chip and usually contains one or more cores. The MCU contains memory and programmable input and outputs giving the MCU control over the entire system. The MCU is used to control everything from collecting data to sending information and managing the system.

Data communication protocols

To control the peripherals, a communication interface is needed. Serial Peripheral interface (SPI), Inter-Integrated Circuit (I2C) and Universal asynchronous receiver-transmitter (UART) are some examples.

In this project, SPI is used. SPI is a high-speed synchronous serial input output port that allows a serial bit stream of programmed length to be shifted into and out of a device. SPI uses a master-slave configuration where one controls and tells what the other should do. SPI can be configured with three of four pins, depending on the configuration. The three pins that are always necessary for SPI communication are, Master In Slave Out (MISO), Master Out Slave In (MOSI) and Serial Clock (SCK). The optional fourth pin is Slave Select (SS). SS is used if the slave needs to sleep between operations or if multiple slaves are operating on the same SPI lines. It is then the SS-signal that wakes up the peripheral and informs it that the communication lines are open for data to be sent and received. SPI is run in Full duplex mode this means that the Connection between the master and slave has separate lines for sending and receiving. The data sent from the master to the slave goes through the MOSI pin whilst data sent from the slave to the master goes through the line MISO pin, [1].
In this chapter, the design of the system is presented including information for the chosen components.

### 3.1 System overview

Figure 3.1 shows an overview of the entire system. The Energy Harvesting part consists of 3 blocks: solar cell, energy management and energy storage. The energy management outputs two different voltages to the different parts of the system, 2.8 V to the NFC-reader and 1.8 V to the MCU. The MCU writes and reads data from the NFC-reader using SPI communication. The NFC-reader is fed from the energy manager with 2.8 V to operate. The NFC-reader communicates with the NFC-tag using a square-loop antenna send and receive information form the tag. When data from the tag is received, the MCU starts the process to forward this data to the server. This is done with the help of the LoRa module integrated with the MCU, The MCU establishes a connection with the gateway using LoRaWAN and the microstrip IFA integrated in the PCB. The data is then sent over to the gateway which passes along this information to the server using a existing WiFi network. The Server collects the data and displays this information to the user.

![Figure 3.1: Block diagram of the proposed system.](image-url)
3.2 Energy harvesting components

In this section, the components chosen to implement the Energy Harvesting system are presented. The parts are, an indoor solarcell from Epishine, a power management system from e-Peas and an energy storage device from Ligna Energy.

Epishine solarcells

As shown previously, the system is supposed to be independent from an external power source. Once mounted, there will be no need to attend to it. This means that batteries will not be an option, unless there is a way to charge them.

Epishine is a brand that specializes in printed organic, for indoor use, solar cells. Solar cells are produced in many different sizes that can be chosen depending on the application. The solar cell size determines how much power they can generated, see Table 3.1 and Figure 3.3. A 50x50 mm solarcell is shown in Figure 3.2.

![Figure 3.2: Epishine solar cell](image)

<table>
<thead>
<tr>
<th>Light intensity and size</th>
<th>50x50 mm</th>
<th>50x30 mm</th>
<th>50x20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 LUX</td>
<td>35</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>100 LUX</td>
<td>75</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>200 LUX</td>
<td>155</td>
<td>94</td>
<td>62</td>
</tr>
<tr>
<td>500 LUX</td>
<td>418</td>
<td>250</td>
<td>167</td>
</tr>
</tbody>
</table>

The solarcell is very thin with a thickness of 0.2 mm making good of application with limited amount of space. The solarcell is also bendable making it ideal for application where the cell is to be integrated to an existing item such as a sculptures or paintings. The solarcell is translucent where the light can travel through the cell. This is why for maximum efficiency, the cell must be placed over a white background that allows the light to go through the cell, reflect on the background, and travel through the cell one more time.

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3.2. Energy harvesting components

The power generated needs to be managed and passed on to the energy storage, this is done using an energy management system constructed by e-Peas. e-Peas is a company specialising in these types of solution whether it is for solar harvesting, Radio frequency harvesting or thermal harvesting.

The e-Peas AEM10941 is a highly efficient regulated dual-output, ambient energy manager for up to 7-cell solar panels with optional primary battery. The AEM10941 is able to charge a storage element as well as distributing the energy at 2 different operating voltages through the two Low-dropout regulators (LDO), Low Voltage Output (LVOUT) and High Voltage Output (HVOUT).

The LVOUT can provide the circuit with 1.2V to 1.8V and a current between 0 to 20mA and the HVOUT can output 1.8V to (batterivoltage-0.3)V and the current 0 to 80mA. Through the three configurable pins the management system can be configured to the applications specification, by defining output voltages and protection levels of the storage element. Three status pins, STATUS[0] to STATUS[2] are used to relay information. In this project only one of the status pins is interesting STATUS[0] that tells the application that the battery is charged enough for the LDO’s to operate. The module is also equipped with both a built in buck and a boost converter, [6]. A simple schematic of the AEM10941 is shown in Figure 3.4.
The module has a couple of configuration pins that can be configured. One configuration that can be made is to enable the high voltage pins and the low voltage pins. The high voltage pin is always enabled, while the low voltage output is disabled. This is because the low voltage output does not generate enough current for the MCU, so the MCU is connected to the buck converter instead. There are also configuration pins CFG[0], CFG[1] and CFG[2]. These pins configure $V_{ovch}$, $V_{chrld}$ and $V_{ovdis}$. $V_{ovch}$ is the maximum voltage accepted by the storage element, meaning when the battery is considered to be “full”. $V_{chrld}$ is the minimum voltage required on the storage element after a cold start. $V_{ovch}$ is the minimum voltage accepted on the storage element, meaning when the battery is considered to be “empty”, [6]. A table of these configurations are shown in Figure 3.6.
3.2. Energy harvesting components

As seen in Figure 3.6, if all the configuration pins are set to 0, custom mode is enabled. Therefore, the voltages can be configured manually by using resistors. This is done by using the following equations:

\[1 \text{M}\Omega \leq RT \leq 100 \text{M}\Omega\]  \hspace{1cm} (3.1)

\[R_1 = RT(1/V_{avch})\]  \hspace{1cm} (3.2)

\[R_2 = RT(1/V_{avch} - 1/V_{chrdy})\]  \hspace{1cm} (3.3)

\[R_3 = RT(1/V_{odis} - 1/V_{chrdy})\]  \hspace{1cm} (3.4)

\[R_4 = RT(1 - 1/V_{odis})\]  \hspace{1cm} (3.5)

where

\[RT = (R_1 + R_2 + R_3 + R_4)\]

Then, R5 and R6 are calculated using the following equations:

\[1 \text{M}\Omega \leq RV \leq 40 \text{M}\Omega\]  \hspace{1cm} (3.6)

\[R_5 = RV(1/V_{hv})\]  \hspace{1cm} (3.7)

\[R_6 = RV(1 - 1/V_{hv})\]  \hspace{1cm} (3.8)

Where,

\[RV = R_5 + R_6\]

Using these equations, the following resistor values were determined. Their values are shown in Table 3.2.

<table>
<thead>
<tr>
<th>Configuration pins</th>
<th>Storage element threshold voltages</th>
<th>LDOs output voltages</th>
<th>Typical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1 1</td>
<td>4.12 V 3.67 V 3.0 V</td>
<td>3.3 V 1.8 V</td>
<td>Solid state battery</td>
</tr>
<tr>
<td>1 1 0</td>
<td>4.12 V 4.64 V 3.0 V</td>
<td>3.3 V 1.8 V</td>
<td>Li-ion/NiMH battery</td>
</tr>
<tr>
<td>1 0 1</td>
<td>4.12 V 3.67 V 3.01 V</td>
<td>2.5 V 1.8 V</td>
<td>Single cell supercapacitor</td>
</tr>
<tr>
<td>0 1 1</td>
<td>2.70 V 2.30 V 2.20 V</td>
<td>1.8 V 1.2 V</td>
<td>Single cell supercapacitor</td>
</tr>
<tr>
<td>0 1 0</td>
<td>4.50 V 3.92 V 3.60 V</td>
<td>3.3 V 1.8 V</td>
<td>Dual-cell supercapacitor</td>
</tr>
<tr>
<td>0 0 1</td>
<td>3.63 V 3.10 V 2.80 V</td>
<td>2.5 V 1.8 V</td>
<td>LiFePO4 battery</td>
</tr>
<tr>
<td>0 0 0</td>
<td>Custom mode - Programmable through R1 to R6</td>
<td>1.8 V</td>
<td></td>
</tr>
</tbody>
</table>
The final calibration pins on the chip are the MPPT pins, the SELMPP[0:1] pins. They are used to select the MPP (Maximum Power Point) tracking ratio. They are set to get the MPPT equal to 85%.

**Ligna Energy**

The energy generated by the solarcells needs to be stored somewhere for it to be accessible when it is needed, this is done using Ligna Energy’s energy storage. Ligna Energy is a company who’s goal is to create a cost efficient, safe and environmentally friendly solution for energy storage. Their energy storage is made of lignin which is a residue material from the forest industry. At the end of its lifetime it can recycled and burned as biofuel. The energy storage can be seen as a capacitance of 0.6 F and has a rated voltage of 2.4 V, the storage device is a good match for low-power iot applications. The lifecycle of the Ligna Energy storage device is rated at more than 10 000 charging cycles or close to 30 years of being charged and discharged once daily giving the user a long lasting and environmentally friendly energy storage solution. Figure 3.7 shows a Ligna Energy storage device.

![Ligna storage device](image)

**Figure 3.7: Ligna storage device**

---

<table>
<thead>
<tr>
<th>Table 3.2: Resistor configuration values</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
</tr>
<tr>
<td>R2</td>
</tr>
<tr>
<td>R3</td>
</tr>
<tr>
<td>R4</td>
</tr>
<tr>
<td>R5</td>
</tr>
<tr>
<td>R6</td>
</tr>
<tr>
<td>$V_{oisch}$</td>
</tr>
<tr>
<td>$V_{ehndy}$</td>
</tr>
<tr>
<td>$V_{oydis}$</td>
</tr>
<tr>
<td>$V_{hbo}$</td>
</tr>
</tbody>
</table>
3.3 Lora-e5

LoRa E5 is a low-cost ultra low-power LoRa module designed by Seeed Technology Co., Ltd. The module is based on the STM32WLE5JC chip made by STMicroelectronics. The STM32WL module consists of an ARM Cortex M4 MicroController Unit (MCU) and a LoRa SX126X bundled together in a System on a Chip (SoC). The MCU is intended for low power application and has a sleep current of only 2.1 µA. The MCU has support for different types of communication with the other peripherals such as Serial Peripheral Interface (SPI), Serial Universal Asynchronous Receiver/Transmitter (UART) and Inter-Integrated Circuit (I2C). This allows the MCU to be used with a lot of different types of peripherals such as sensors or as in this project a NFC reader, [24].

3.4 MFRC522

The MFRC522 is a reader/writer Integrated Circuit (IC) made for contactless communication at 13,56 MHz. The chip supports ISO/IEC 14443 A/MIFARE and NTAG, making sure it can read and write to many different types of tags. The chip has support for different types of communication with the MCU such as SPI, UART and I2C. The chip needs 2.5 V to 3.3 V to operate, [22]. and will draw 163 mA when it is active. To reduce power consumption overall the RC522 chip will be turned off when not in use. From the antenna side the RC522 chip has an input impedance of 40 Ω, the antenna must be matched to this to reduce reflection and losses in the circuit.

3.5 Antenna Design

In this section, the design process of the two antennas will be explained. The antennas were designed and verified in Advanced Design System (ADS). The input impedance matching was performed and the antenna parameters were examined and evaluated. The antenna designs in form of layout were then exported to Altium designer. Originally, the PCB had two layers but then two more layers were added. The substrate parameters are shown in Table 3.3 and the substrate is shown in Figure 3.8, where the conductor layers are copper. The thickness of the copper layers is 18µm.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\epsilon_r$ (dimensionless)</th>
<th>$\tan\delta$ (dimensionless)</th>
<th>height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>4.6</td>
<td>0.01</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 3.3: Substrate parameters

![Figure 3.8: Substrate](image)
Inverted-F Antenna Design

As mentioned in Section 2.4, Inverted-F antenna (IFA) is a folded monopole antenna. The IFA is designed to resonate at the frequency 868 MHz, which is a relative low frequency. For a half wavelength monopole antenna, the wavelength is $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{868 \times 10^6} = 0.346 \text{ m}$ and then the length of the antenna will be approximately 17 cm. To minimize the IFA antenna, the open end of the antenna is altered. The layout of the antenna is shown in Figure 3.9, where the dimensions are shown in Table 3.4. Since the IFA is so dependent of the ground plane, the antenna was designed after the rest of the PCB layout was finished, so that the ground plane size is already set.

![IFA Layout](image)

Figure 3.9: Layout of IFA

<table>
<thead>
<tr>
<th>L1</th>
<th>20.00 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>L3</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>L4</td>
<td>6.0 mm</td>
</tr>
<tr>
<td>L5</td>
<td>10.00 mm</td>
</tr>
<tr>
<td>W1</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>W2</td>
<td>1.0 mm</td>
</tr>
</tbody>
</table>

Table 3.4: IFA dimensions

The IFA design began from the estimated length of 17 cm. Then, this length was tweaked to get a meandered geometry to minimize the size of the antenna while keeping the antenna performance the same.

The antenna performance is analyzed mainly by looking at the S11 S-parameter. Generally, S11 is the ratio between the amplitude of the reflected signal at port 1 to the magnitude of the input signal applied to port 1, when the other ports are terminated with matched loads, [Ref please!]. In other words, S11 is also the reflection coefficient, [Reference, please!]. More practically, the reflection coefficient gives information about the input impedance at port 1,
as shown by the definition of $S_{11}$:

$$S_{11} = \Gamma_{in} = \frac{(Z_{in} - Z_0)}{(Z_{in} + Z_0)} \quad (3.9)$$

As antennas are usually designed for a specific input impedance, usually $50 \, \Omega$, a low value of $S_{11}$ shows that the antenna is matched to $50 \, \Omega$.

In Figure 3.10, simulation results for the antenna are shown. In the graph to the left, it can be seen that at 868 MHz, the $S_{11}$ S-parameter is $-17.9$ dB. This corresponds to $S_{11} = 10^{-17.9/10} = 0.016 = 1.6 \%$, i.e., 1.6 % of the incoming signal amplitude is reflected back to port 1. It can also be seen that the bandwidth of the antenna estimated at $-10$dB is around 60 MHz.

The graph to the right shows the phase shift at different frequencies. It can be seen that the resonance of the antenna appears at the desired frequency. Where, the resonance is generally defined as the point where the phase suffers a jump between $\pm 180^\circ$.

![Figure 3.10: IFA simulation results](image)

First simulation results show that the antenna resonates at the desired frequency, but it can be better matched to $50 \, \Omega$. The matching network is designed using lumped components. This is done, on one side because the operation frequency is too low and a transmission lines matching network will be too large. On the other side, if the antenna does not work as intended, it will be easy to replace the components for better matching. However, still a feeding transmission line of $50 \, \Omega$ characteristic impedance is needed. The transmission line is designed for the specific substrate, operation frequency in ADS, and the result of the design is the width of the line corresponding to $50 \, \Omega$, see Figure 3.11, the broader line.

For further generating the lumped matching network, the antenna was generated as a layout component, i.e., electromagnetic (EM) simulation data behind a symbol that looks alike the layout of the antenna. This layout component was then imported to a schematic in ADS. Using the Smith Chart Tool in ADS, a two component matching network consisting of one inductor and one capacitor was generated. The lumped component matching network is connected to the $50 \, \Omega$ transmission line that corresponds also to the micro controller port. The nominal values of the $LC$ components were adapted to values from the E12 standard, i.e., a shunt capacitor with the value $C = 3.6$ pF and a series inductor with value $L = 27$ nH, see Figure 3.11.
Simulation results when the antenna matching network was used can be seen in Figure 3.12. In the right graph, it can be seen that the new value of S11 at 870 MHz is -23 dB. This a better value than the value corresponding to the antenna without matching network. The graph to the right represents S11 plotted in a Smith chart. The frequency varies from 100 MHz to 1 GHz. The marker $m_2$ is placed at 870 MHz. It can be observed that at 870 MHz, the reflection coefficient is practically zero and the input impedance of the antenna with matching network $Z_{\text{in}}$ is $50 \, \Omega$. This means that the antenna is well matched to $50 \, \Omega$. More exactly, the simulation indicates the "impedance = $Z_0*(0.870 + j0.018)$", where $Z_0 = 50 \, \Omega$.

Figure 3.12: Simulation results: IFA with matching network.
As mentioned in Section 2.4, there are several antenna parameters to consider and examine. In ADS, far-fields of the antenna can be examined in a 3-dimensional (3D) representation and other antenna parameters can be obtained. The radiation pattern of the IFA at 868 MHz can be seen in Figure 3.13. The antenna is oriented as shown in Figure 3.14, where arrows indicating the current flow are also visualized. It can be seen that the radiation occurs orthogonal to the antenna surface in positive and negative z-direction. This is also the purpose of the IFA design, assured by the fact that the antenna does not have a ground plane on the bottom plane to which the fringe fields couple to.

In addition to the 3D the radiation pattern, a 2D-cut can be done to get a 2D-representation of the radiation pattern. This can be seen in Figure 3.15. In this graph, the radiation pattern was cut around the y-axis and the antenna Gain and Directivity can be observed. The maximum Directivity is 2.242 and the maximum Gain is 1.439.
3. DESIGN, MEASUREMENTS AND IMPLEMENTATION

Figure 3.15: Simulation results: IFA radiation pattern, 2D-representation

As a summary of the antenna simulation in Momentum, all antenna parameters are shown in Figure 3.16. Here, it can be seen that the radiation efficiency is 83%. This is though a simulated result for the case when the environment is optimal. In practice the radiation efficiency will not be this high. The Gain and Directivity can also be seen in Figure 3.16. The gain is close to 1 which means that the antenna is omni-directional. Fact that can be seen also in 3.15. The theory about the antenna Gain presented also in Chapter 2, is saying that high gain indicates a more "directional" antenna and low gain gives corresponds to an omni-directional antenna. Recall also that directivity and gain are similar to each other. Overall simulated parameters show that the antenna works as intended, the radiation pattern looks as expected and the radiation efficiency is optimal.

Figure 3.16: Simulation results: IFA parameters, from ADS.
3.5. Antenna Design

After the design in ADS, the final result will be the layout of the antenna including the feeding line and the matching network with information about the nominal values of the matching network components. As explained previously, the antenna was designed first after the size of the ground plane was finalized so that the antenna can be optimally integrated with the rest of the system on the same PCB.

Square-loop antenna design

As mentioned in Section 2.4, in this project, the square-loop antenna is not really an antenna. This makes typical antenna theory and design not viable for this antenna. E.g., usual antenna parameters are not important. The parameter that is important is the inductance of the antenna. For the design, ST Microelectronics’s guide was used, [12], i.e., mainly the theory for calculation of the antenna inductance value. Using the equation for square-loop antenna, the inductance that resulted was 1.2 mH. This is a too high value and it was appreciated as unreasonable. Therefore, another near-field communication (NFC) antenna design tool was used. It is an NXP tool, [4]. Design results for this antenna are shown in Figure 3.17. With the dimensions and spacing calculated for the specified substrate (PCB), the inductance of the antenna is 1.3 µH. This is a more realistic value considering that a rule of thumb is that the antenna should have an inductance of at least 1 µH, as mentioned in Section 2.4.

This design was then implemented in ADS, and the layout is shown in Figure 3.18. Since a square loop antenna is not really an antenna, and standard antenna parameters do not apply here, the main factor to take into account is the inductance. The inductance mainly depends on the total area of the antenna and the amount of turns.

![Figure 3.17: NXP Antenna Tool result, [4]](image-url)
The dimensions of the antenna are shown in Figure 3.18 and the values are summarized in Table 3.5. These values are verified in the NXP antenna design tool. The self resonant frequency is 97 MHz. This is not a factor that matters because with a matching network the antenna will induce current with the carrier frequency 13.56 MHz.

<table>
<thead>
<tr>
<th>L1</th>
<th>40.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2</td>
<td>31.2 mm</td>
</tr>
<tr>
<td>L3</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>L4</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>N</td>
<td>4 turns</td>
</tr>
</tbody>
</table>

In the NXP antenna design tool there are functions that enable the design of matching networks and filters. An example of the system including the antenna, matching network and an EMC filter is shown in Figure 3.19.

The EMC filter is used to protect the circuit from electromagnetic interference that can be caused by the presence of high frequencies components or frequency spikes. In this case and as shown in Figure 3.17, the self resonant frequency of the antenna is 97 MHz. This means that the antenna will naturally resonate at 97 MHz and hence, will harvest signals at this frequency. This is not desired, therefore the presence of the EMC filter, that will remove those signals from the system.

The co-simulation set-up in ADS consisting of the antenna, EMC filter and the matching network is shown in Figure 3.20. To summarize, the EMC filter was designed as a low-pass filter with a cut-off frequency of 21 MHz using lumped components. Then, the EMC filter and the matching network were matched to 40 \( \Omega \), which is the input impedance of the MFRC522. The start values for these components were taken from the NXP antenna tool, then optimized in ADS to match the antenna at the desired resonance frequency which is 13.56 MHz. The nominal values for the components of the matching network and EMC filter are shown in Table 3.6.

![Figure 3.18: Square loop antenna layout in ADS](image-url)
3.5. Antenna Design

Figure 3.19: NFC antenna, matching network and the EMC filter, typical example, [21]

Figure 3.20: Square loop antenna with matching network and EMC filter in ADS.
Table 3.6: EMC filter and matching network values

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>4.7 µF</td>
</tr>
<tr>
<td>C2</td>
<td>4.7 µF</td>
</tr>
<tr>
<td>C3</td>
<td>200 pF</td>
</tr>
<tr>
<td>C4</td>
<td>200 pF</td>
</tr>
<tr>
<td>C5</td>
<td>13 pF</td>
</tr>
<tr>
<td>C6</td>
<td>16 pF</td>
</tr>
<tr>
<td>C7</td>
<td>56 pF</td>
</tr>
<tr>
<td>C8</td>
<td>56 pF</td>
</tr>
<tr>
<td>L1</td>
<td>1 µH</td>
</tr>
<tr>
<td>L2</td>
<td>1 µH</td>
</tr>
<tr>
<td>L3</td>
<td>1 µH</td>
</tr>
<tr>
<td>L4</td>
<td>1 µH</td>
</tr>
</tbody>
</table>

As mentioned before, typical antenna parameters are not examined to determine the performance of the square-loop antenna. Therefore, there is no way in ADS to verify the antenna design other than the quality of the matching. This is because ADS only supports far fields simulations to examine antenna parameters such as radiation efficiency, and for the near-field antenna in this case, antenna efficiency is practically zero.

Hence, for this design it is of importance to perform S-parameters simulations for the two ports of the antenna, see Figure 3.20. The third port in the middle represents the ground. The simulation results are shown in Figure 3.21, where the upper graphs are for port 1 and the bottom ones are for port 2. They show the reflection coefficients in form of S(1,1) and S(2,2). Reflections to port 1 and port 2 are attenuated by approximately -17 dB, a value that is efficient. This is shown also in the Smith chart graphs to the right, where it is more clear that the input impedances at port 1 and port 2 are properly matched. The bandwidth of the two antennas at both ports is narrower than that of the inverted-F antenna. This is not critical. This is because the square-loop antenna is in fact an inductor and the communication between the reader and the tag occurs when they are coupled.
3.5. Antenna Design

These simulation results have shown good matching and filtering of other signals. They proof that the antenna should work by theory.

To conclude, a square loop antenna design is a classical planar inductor ($L$) design, where the specification that is needed to be considered is only the $L$-value. If the antenna should have been manufactured, some measurements could be performed to verify the inductance value. By theory, the magnetic field should revolve around the antenna to then couple to the receiver antenna of the NFC tag. At this frequency, lumped components were used to implement the rest of the circuitry (matching networks and EMC filter) for smaller occupied area of the device. Moreover, this allows also easy exchange of values, if needed.

Figure 3.21: Simulation results, S-parameters for square loop antenna circuit.
3.6 Theoretical calculations

To determine if the system is possible as specified, theoretical calculations of power consumption have been made. The data used for these calculations was taken from the data sheet of the used components and circuits. To calculate total power consumption, both the LoRa-e5 and the RC522 need to be taken into account, see (3.10).

\[ E_{\text{tot}} = E_{\text{lora}} + E_{\text{RC522}} \]  

(3.10)

\( E_{\text{lora}} \) is divided into two parts, \( E_{\text{lora, transmit}} \) when the LoRa-e5 is active and \( E_{\text{lora, sleep}} \) when LoRa-e5 is sleeping. This can be seen in (3.11) and (3.12), where \( I \) is current (A), \( T \) time (s) and \( U \) the input voltage of 1.8 V. The two parts are then combined to calculate the total energy consumption as shown in (3.13).

\[ E_{\text{lora, transmit}} = (I_{\text{lora, transmit}} \times T_{\text{lora, transmit}}) \times U_{\text{lora}} \]  

(3.11)

\[ E_{\text{lora, sleep}} = (I_{\text{lora, sleep}} \times T_{\text{lora, sleep}}) \times U_{\text{lora}} \]  

(3.12)

\[ E_{\text{lora}} = E_{\text{lora, sleep}} + E_{\text{lora, transmit}} \]  

(3.13)

Only active time needs to be considered when calculating power consumption of RC522 RFID-reader. This is due to the RC522 only being powered on when it is in use. The voltage is only feed to the chip when it is in use, when the information reaches the MCU, the power to RC522 is cut and it therefore does not draw any power when it is not in use. The calculation of power consumption for the RC522 chip can be seen in (3.14). The calculations are similar to calculations for power consumption of LoRa-e5, but the input voltage is different at 2.8 V instead of 1.8 V feed to the MCU.

\[ E_{\text{RC522}} = (I_{\text{RC522}} \times T_{\text{RC522}}) \times U_{\text{RC522}} \]  

(3.14)

To calculate how much power the solar cells produce, (3.15) is used. The equation uses the power generated at a set light intensity and multiplies it with the time it charges.

\[ E_{\text{storage}} = P_{\text{LUX}} \times T \]  

(3.15)

To calculate how long time it takes to charge up the battery after every transmission, a set of equations must be used. Equation (3.16) is used to calculate how much power the MCU draws in sleep mode. Equation (3.17) calculates the power consumption for one active cycle including collecting data from the tag and transmitting this data to the server. Equation (3.18) is used to calculate the time it takes to charge the energy storage back to full capacity given the Power produced from the solar cell and the power consumed by the MCU in sleep mode.

\[ P_{\text{lora, sleep}} = (I_{\text{lora, sleep}} \times U_{\text{lora}}) \]  

(3.16)

\[ E_{\text{active}} = E_{\text{lora, transmit}} + E_{\text{RC522}} \]  

(3.17)

\[ T_{\text{after_TX}} = \frac{E_{\text{active}}}{(P_{\text{LUX}} - P_{\text{lora, sleep}})} \]  

(3.18)
3.7 Measurements

Measurements have been done to investigate how much power can be produced in different locations, given different circumstances e.g., different painting sizes or painting’s positions that can be close or not to a window. The measurements were taken in Vrinnevisjukhuset, Norrkoping. The hospital is run by Region Östergötland. There are a lot of paintings hanging in the hospital hallways and it is in these hallways that measurements of light intensity were taken using a lightmeter. A lightmeter is a device that measures light intensity in the unit LUX. Some of the paintings chosen for these experiments had lights directly pointed to them, some were close to windows where the outdoor light would come in, and finally, some paintings had both or neither. All of these different lighting environments were measured and compared. The light intensity was measured with two different angles of the lightmeter. Light was measured with instrument laying on the painting, pointing straight up to the ceiling, as seen in Figure 3.22. In the other measurement, the light meter at the same painting but angled towards the light, see Figure 3.23. These tests were done to estimate for different light conditions and object’s positions in space how long the system must charge between each transmission and if the energy storage device is necessary.

Figure 3.22: Light measurement with lightmeter laying flat on the painting

Figure 3.23: Light measurement with lightmeter laying at an angle on the painting
3.8 Software

In this section, the setup of the MCU and how it was programmed will be explained. This is done explaining the setup process and a flowchart visualizing the programming.

The first prototype was developed using the LoRa-e5 mini development board from Seeed Studio. LoRa-e5 is based on the STM32WL MCU. It can therefore be programmed using a software called STM32CubeIDE. STM32CubeIDE is a C/C++ development software for STM32 MCUs. With this development software, the developer can choose the MCU existing under the selection tab and then specify what they want to use on the MCU, e.g., the clock speed, communication (uart, spi, i2c, GPIO), LoRa and all of its parameters. The IDE then generates the base code for the options the developer has made and thus a project is set-up where the development can start. To transfer the code from the computer and actually run it, a ST-LINK v2 is needed with a software called STM32Programmer.
STM32Programmer is a software created by ST Microelectronics that can both upload code to the device and read the devices memory. Before the MCU can be programmed, there are a few steps necessary to be taken. At first, the development board has a preloaded code using AT-commands through the UART to assure communication back and forth between a computer and the device. (The AT is an ATTENTION command and is used as a prefix to other parameters in a string. The AT command combined with other parameters can be set up in the communications package or typed in manually as a command line instruction.) Then, the board needs to be connected to the computer with a USB cable and a serial monitor of choice can be opened. The serial monitor must be setup with a baud rate of 115 000 to write some AT commands. The AT commands AT+ID = DevEui and AT+ID = AppEui gives the user the needed keys for the communication with the LoRa server. To upload the code, the device must med flashed to remove the software provided by the manufacturer. Also, the read protection must be changed from BB to AA so that to be able to read and write code to the MCU.

The Things Stack (TTS) is used to setup the LoRa server, where the data sent from the system is displayed. This is done through a LoRa gateway. The gateway chosen for this project is The Things Indoor Gateway (TTIG) and is a low-cost LoRaWAN gateway with WiFi as the backhaul. This gateway offers the user a good development environment, with a simple setup procedure and a small form factor giving the user the possibility to easily move the gateway to different places.

To setup the gateway, two steps are required. Firstly, the gateway needs to be connected to the local WiFi. Secondly, the device needs to be connected to TTS. This is done through their website, [16]. When these steps are performed, the LoRaWAN is setup and ready to be used. Next step is to create an application so that the MCU can communicate with the server through the gateway. To add an end node to the application three Keys are necessary: Device EUI (DevEui), Application EUI (AppEui), and Application Key (APPKEY). DevEui and AppEui are got from the earlier AT-commands while APPKEY is set by the user. After the two steps are completed, the end device should be able to communicate with the gateway and server. A RC522 module was used when developing the system. The RC522 module is a complete NFC reader/writer with a square-loop antenna. The module is build around the

![Figure 3.26: The things Indoor Gateway](image-url)
chipset MFRC522 mentioned in Section 3.4 and uses SPI to communicate with the MCU. For this to work, the source code needs to be written. I.e., the code initializes the circuit and then, through the master-slave communication, the data stored in the buffers on the NFC-tags is stored. The data that is then being sent is the manufacturer assigned Unique IDentifier (UID) code attached to the NFC-tag. The UID is then sent form the board through the gateway to the server where the data is displayed as a 4 bytes. The code starts with the initialization of the different subsystems. I.e., the clocks are started and the MCU is setup to the specified settings. This includes appointing what inputs/outputs will be activated and what they are going to do. This is followed by initialization of the peripherals, e.g., the NFC reader to be ready for scanning the tag. After this is done, the LoRa process starts. The end node tries to establish a connection to the gateway by sending a join request. If the gateway accepts, the end node and gateway will be connected. Else, the end node will send another join message. When the end node and the gateway are connected, the MCU can start collecting and sending data to the server. The MCU collects data from the NFC-tag using the NFC-reader. The data is then sent to the server through the gateway. After the data has been sent, the system goes into sleep mode and waits for the next transmission time. This is visualized in Figure 3.27.

![Flow chart of end node start to establish communication with gateway](image)

Figure 3.27: Flow chart of end node start to establish communication with gateway
4 Results and Discussion

In this chapter, main results of this work are presented. The choice of the system architecture and of the communication standard is explained. Light intensity measurement results and calculation of the power consumption are presented to estimate how often the system can be active. The complete schematic in Altium Designer is shown as well as the complete PCB layout including the integrated antennas. Finally, some test results that proof the programming of the communication are shown.

4.1 System architecture

One of the main purposes of this project was to determine what type of architecture was optimal for this application. It is necessary that the system can be used in many different types of buildings, therefore a reconfigurable solution that can be used in these buildings is important. In Chapter 2, two different architectures were presented, Architecture 2 was chosen due to the wide range of application. For Architecture 1, the system needs to be attached to the painting and one needs to know at what wall it is hanging on. This implementation would require a node in each room to determine where this painting hangs. This kind of system might be appropriate in a building with paintings concentrated in one room, but would require many nodes in buildings with paintings spread over multiple rooms. Architecture 2 solves this by splitting the system into two parts, one hanging on the painting and one hanging on the wall. By separating the system into two parts, the wall and painting get unique identities that can be then sent to a server to determine the position and what painting is hanging at that position. This is a good solution since the project specification indicates that the system is not a security system, but a inventory tool, meaning that the art does not need to be tracked. The system is only there to make sure that the paintings are hanging at the specified location and was not moved around.

4.2 Wireless communication standards

Multiple wireless communication standards were considered for this project and presented in Section 2.3. The two standards best suited for this type of system, were BLE and LoRa. Similarly to the system architecture, a configurable setup which is applicable at multiple different types of buildings and environments is necessary. BLE is a good low cost solution for
places such as a museum that have a lot of paintings collected at a single room. However, due to the short range of BLE, multiple gateways would be necessary to collect data from the paintings in buildings such as hospitals and other institutions were the paintings are spread out over a large area. LoRa was chosen for this project. The combination of long range, low power consumption and low cost, made this standard a good choice for this project. With a range up toward 10 km, a single strong gateway could be located in the center of the building and collect data from all the end nodes. This would require less modification to the existing infrastructure as well as easy expansion if for example, more paintings would be added. In this project, the TTIG was chosen as a gateway, mainly due to the portability and low cost of the device. The gateway also had direct support to TTN, which makes it easy to display the received information from the end nodes.

4.3 Measurement results

As seen in Section 3.7, measurements were made to determine the light intensity at different locations in Vrinnevisjukhuset. The results obtained from the measurements are shown in Table 4.1 for different light conditions. They show as expected that, dependant on the location of the painting, the difference between the light intensity can be large. E.g., the measurements taken on a bright day for painting "JR" is very high. But, measurements on paintings with no direct light, having only the ambient light show only 40 LUX light intensity. Variation from 40 LUX to 475 LUX could be observed in summer time, which gives an information about the range of expected light intensity in an environment where the system will be used.

Table 4.1: Measurement data measured from Vrinnevisjukhuset.

<table>
<thead>
<tr>
<th>Artist</th>
<th>Paintings name</th>
<th>Light intensity (LUX)</th>
<th>Laying flat</th>
<th>Laying at an angle</th>
<th>Light environment</th>
</tr>
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<tbody>
<tr>
<td>Stina strandberg</td>
<td>&quot;Kärna&quot;</td>
<td>74</td>
<td>90</td>
<td></td>
<td>Close to window, no direct light</td>
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<tr>
<td>Eva Löfdahl</td>
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<td>337</td>
<td>475</td>
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<tr>
<td>Peter Tillberg</td>
<td>&quot;öronsten-80&quot;</td>
<td>231</td>
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<td>40</td>
<td>40</td>
<td></td>
<td>Far from window, no direct light</td>
</tr>
</tbody>
</table>

4.4 Theoretical calculations

To determine the interval between the transmissions, the equations presented in Section 3.6 were used. Table 4.2 shows how long it takes for the energy storage unit to completely charge, given a light intensity. The table shows that a transmission can be made every six hours when the light intensity is 50 LUX. This means that one transmission can be made a day given that the solarcell can capture light 8 hours a day.

Table 4.2: Calculation results.

<table>
<thead>
<tr>
<th>Charge</th>
<th>Charge after TX</th>
<th>Entire battery capacity</th>
<th>50 LUX</th>
<th>100 LUX</th>
<th>200 LUX</th>
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<tr>
<td>Entire battery capacity</td>
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<td>2.6</td>
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<tr>
<td>Entire battery capacity</td>
<td>31.4</td>
<td>13.8</td>
<td>6.5</td>
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</table>
4.5 Art Stocktaking Using IoT

The proposed system circuitry mainly consists of the three ICs: the energy harvesting unit, NFC-reader and the MCU. The schematic in Altium Designer is detailed in Figure 4.1. With reference to Figure 4.1, some comments are given as follows:

1. These resistors are for calibrating the low-dropout regulators (LDO) on the AEM10941. The voltages that are calibrated here are $V_{ovchr}$, $V_{chrdy}$ and $V_{ovdis}$.

2. These resistors are for calibrating the $HVOUT$ pin, determining the voltage that is fed from the pin. In this case the voltage is 2.8 V.

3. MOLEX connectors where the batteries are inserted. The $BAL$ is the mid point connection for the super capacitors.

4. These are 0 Ω resistors that are connected to the configuration pins so that the AEM10941 can be configured manually, after production.

5. Here, the matching network and the EMC filter of the square-loop antenna can be seen.

6. The crystal oscillator that generates a signal with the frequency 27.12 MHz. The oscillator is needed as an external clock since the MFRC522 does not have an internal clock.

7. Switches that are connected to the status pins of the AEM10941. The status pins are not directly connected to the MCU as the current may leak from the MCU. Therefore, switches are connected so the pins are completely off until they turn on.

8. The matching network for the IFA.

9. These are fiducial markers that work as reference points for the machines when PCBs are manufactured.

For clarity, and with reference to Figure 4.1, the following main circuits are detailed. The yellow colored circuits, from left to right are:

1. AEM 10941: solar power management IC, from e-Peas
2. LoRa-e5: MCU and LoRa transceiver
3. MFRC522: highly integrated reader/writer IC for contactless communication at 13.56 MHz.
The layout of the final PCB is shown in Figure 4.2. The dimension of the PCB is 13 cm x 7 cm. It can be seen that both antennas are integrated on the PCB as being placed outside the ground plane. The PCB is a four-layer PCB. There are some decoupling conductors and also buttons and connectors for programming the MCU. There are some other dummy components that are usefully for the further development and debugging of the system. It is assumed that these components will be not present in a finalized product, e.g., $0 \Omega$ resistors as striving for an optimal layout of small area.
4.6 Software

Communication was established between the end node and the server. Information could be sent from the end node and received at the server. This test was made by manually specifying the bytes being sent. The end node connects to the gateway and sends data, with a time interval specified in the code. When the node has sent the message, it will enter the sleep mode until next transmission. This reduces the overall power consumption and makes it so that the harvested power is enough to power the system. The message to the server that was added manually is seen in Figure 4.3, i.e., 8 bytes added to the buffer. Figure 4.4 shows how the information is visualised on the server. The DevAddr shows which end node the information is sent from, and MAC Payload show the information sent from that end node. The code is set to send out this information every 10 s, but can be specified to other values in the code by the user.

```c
595  AppData.Buffer[i++] = (uint8_t)(0xAA);
596  AppData.Buffer[i++] = (uint8_t)(0xAB);
597  AppData.Buffer[i++] = (uint8_t)(0xAC);
598  AppData.Buffer[i++] = (uint8_t)(0xAE);
599  AppData.Buffer[i++] = (uint8_t)(0xAF);
600  AppData.Buffer[i++] = (uint8_t)(0xBA);
601  AppData.Buffer[i++] = (uint8_t)(0xBB);
602  AppData.Buffer[i++] = (uint8_t)(0xBC);
603  AppData.Buffer[i++] = (uint8_t)(0xBD);
```

Figure 4.3: Data specified in code

Figure 4.4: Visualisation on server
As mentioned in Chapter 1, the purpose of this master thesis was to investigate and design a stocktaking system with IoT capabilities. Through design it is meant the process consisting of: proposed block diagram, choose of the appropriate hardware and communication standard, design and simulations of the antennas, different calculations, software development, layout of the PCB with integrated antennas. The realization of the complete PCB is called implementation of the system.

The project started with a literature study to investigate the possible solutions for this typical application. After literature study, a system was proposed. The chosen architecture, in this project called Architecture 2, makes use of both LoRa and NFC communication standards. Architecture 2 was chosen for its potential to be implemented at a low-cost as a simple but complete system. The system in this form does not require too complex, expensive hardware. The LoRa communication was mainly chosen for its long range capabilities. Since the end product will be installed at many different locations, it was also important that the system can be used given different building types.

The proposed system consists of three main blocks, i.e., the energy harvesting, the MCU, and the NFC-reader. The energy harvesting consists of a) the Epishine photovoltaic cell, b) the storage unit from Ligna Energy, and c) the energy management circuit from e-Peas. LoRa-e5 MCU has a built in LoRa module and the capabilities of a STM32 processor. The system then used a RC522 to collect data for a NFC-tag attached to the painting and relayed this information to the server operated by TTN.

To understand if the system would work and correspond to the low-power consumption requirements, measurements of light intensity and calculations of power consumption have been done. It was decided that the RC522 chip would be turned off when it was not in use to further reduce the current consumption during sleep mode. These calculations indicate that the system can sample and transmit data once every day if the light intensity is 50 LUX.

Two antennas were designed and simulated in ADS: one IFA at 868 MHz for LoRa communication and one square-loop antenna at 13.56 MHz for NFC communication. The antennas were then transferred over to Altium Designer to be integrated with the rest of
system circuitry on the same PCB.

As the Bill of Materials (BoM) was completed for the entire system, the layout of the PCB was designed in Altium Designer. The design resulted in a four-layer PCB with two routing layers, one ground layer and one power layer. The four layers result in more flexibility to integrate the antennas with the rest of the hardware, i.e., to make sure that the IFA antenna gets a good ground plane that is not interrupted by connections between the components. After some iterations, the PCB was ordered. However, at the end of the master thesis time period, the PCB did not arrive. Hence, the implementation phase was postponed. At the time of writing this text, the components are to be ordered.

Software was developed for the MCU to enable communication with the server through the gateway, and then to transmit bytes of information after a certain time. Testing this functionality, it was shown that the code was functional. Also, a first attempt to integrate the NFC reader with the MCU was made, but it was unsuccessful. More time should be necessary to perform this step. This lack of time is due to the delayed start of software development that was caused in turn by the late arrival of both the gateway and the NFC-reader. To the end of the project, the delays of getting on place the necessary hardware became a problem caused by discontinuities in the planned project flow due to the summer vacation at the company. Also, the SPI code between the MCU and NFC-reader was not completed.

5.1 Further Work

As shown previously, there is still some work to be done before this project can result in a physical prototype. On the software development: The code needs to be completed meaning the NFC-reader should be able to read data from the tag and send this data to the MCU. After that, the code could be optimized to further reduce power consumption. One example of how this could be done is, changing from OTAA to ABP. This is a solution since the nodes and gateway are stationary when the system is installed.

The PCB can be made smaller by removing things that are not important for the function of final product. The first PCB for the prototype system includes things that will be not required for the final product. They are now important for further development and optimization of the system. E.g., the pins for the UART interface are needed if debugging of the system is required, but will be unnecessary for the final product. Another thing that could be removed are the 0 Ω resistors added to be able to change the configuration of the e-Peas module.

Further test should be conducted to see if the antennas need to be optimized or if other components should be replaced by more energy effective components. Test of the real power consumption is also necessary to estimate the real interval of transmissions.
Bibliography


# Bill of materials

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<th>Item</th>
<th>Qty</th>
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<td>Linear</td>
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Figure A.1: Bill of materials
Power layer of PCB

Figure B.1: third layer of PCB