Towards Continuous Sensor Operation: Modelling a Secured Smart Sensor in a Sparse Network Operated by Energy Harvesting

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Abstract: In modern society sensors are omnipresent. They gather information about their environment in order to optimize production flows, minimize energy usage, learn about the environment, or maximize the owner's comfort. To achieve the desired goal in already existing buildings, sensors are introduced afterwards. These sensors might not be able to connect to a sensor network because of obstacles or user policies. If this happens, other mechanisms to create a network to gather the data need to be found. Additionally, these sensors should last for a long period and are therefore probably powered using energy harvesting methods. In this paper we present an approach for simulating the charging process of such sensors and connecting them to a network using mobile communication partners.

1 Introduction

In our society we use sensors to automatically gather data for almost every aspect of our environment. In some applications the sensors cannot connect to a network, either it is not feasible to build infrastructure to connect the sensors (1) or they are not allowed to join an existing network (2).

The first use case is most likely to arise in a sparse sensor network such as when monitoring a wide area or if obstacles such as buildings influence the communication channel. Furthermore, this can arise in an Industry 4.0 setting where sensors can be added at any time and due to insufficient wireless coverage, interferences, obstacles, or policies the sensors cannot connect to the local network.

In the second case the sensors can collect data that needs to be handled confidentially and are therefore not allowed to be transmitted over a long-range wireless communication channel. This can also happen in an Industry 4.0 scenario.

For these use cases mobile communication partners (nodes) with additional computational power and further capabilities can be introduced to connect the sensor nodes to the data sink. These mobile partners can be a worker or robot in a factory, a home owner in his house, or an employee of the city. These communication partners then need to estimate the urgency of the collected data, the memory usage of the sensor, and the energy level of the sensor nodes they should connect to the network. This results in periodical visits from the mobile node at any sensor. These visits can furthermore be used to prolong the sensor's operational time without much effort.

Additionally, when the nodes are visited and their data is collected by the mobile node it may also be possible to configure the sensors behaviour to account for changing needs of the owner. To mitigate possible threats that come from unauthorized personnel changing the configurations, the sensors need to be secured.

There are many proposed solutions that connect the sensors to mobile nodes (eg. (Marta and Cardei, 2009; Ye et al., 2002; Kim et al., 2003)). Most of these use traditional radio frequency communication to communicate the distance to the mobile node. Transporting energy in addition to the data requires other communication technologies such as Near Field Communication (NFC). In this work we examine the possibility of using NFC-enabled robots, or NFC-enabled smartphones to charge, read out, and configure sensor nodes which cannot be connected in a traditional way. This should happen while the data is gathered reliably and secured.

The design of such sensor nodes poses many complex questions such as: "Where is the energy needed the most?", "How much energy can be saved by reducing the sample frequency?", or "How can the energy be used more effectively?". To answer these questions, simulations can be used to gain insights in this complex topic. These simulations focus on the detailed description of the sensor system and try to give detailed answers. This however neglects other major questions such as: "How does the designed energy harvesting system perform?" or "How does the environment affect the sensor communication?".

This publication focuses on the creation of a simulation that is also able to answer questions like these. To do this we created a simulation that focuses on the gathering of time insensitive information using sensor nodes in an environment that does not allow long range wireless communication. Such scenario might arise when measuring the temperature in an automated warehouse, the air humidity of a basement, or the air quality in a city. In these scenarios, some agents (robots or humans) constantly move through the environment performing operations. We propose that they can also collect the information from the sensor nodes, keep them operational and adapt the sensor nodes behaviour while these agents are performing their jobs.
To effectively use such a method requires the prior knowledge of the sensors energy consumption. This is necessary as the sensors operational lifetime is limited by the stored energy. The periodic visits should happen shortly before the internal memory is full or the energy level drops below a certain level to optimally use the mobile agent's time. Thus, this publication explores a method to estimate the energy consumption of a smart sensor and the possibilities that energy harvesting offers to prolong the sensors lifetime.

The remainder of this paper is structured as follows: In Section II related work is described. This section is split to emphasize the energy harvesting, the energy usage estimation and the mobile data collection. The theory and approach of our experiments can be found in Section III. Here we describe the hardware prototypes, experiments and the performed simulations. Section IV is dedicated to the measurements taken with the prototypes and compares it to the results of the simulations. Section V contains ideas on how to improve on the findings of this paper. This paper concludes in Section VI.

2 Related Work

2.1 Energy Harvesting

Prolonging a battery powered sensor's lifetime is the goal of many publications. Most of the publications include mechanisms for harvesting energy from the surrounding. These harvesting methods include the use of solar cells (Chen et al., 2010) or antennas (Pinuela et al., 2013) to use electromagnetic radiation, devices to convert heat gradients (Dziurdzia and Stepien, 2011) to electrical energy, and mechanisms to utilize mechanical energy (Choi et al., 2006).

All those methods are built to support the sensor with a steady (or at least calculable) amount of energy. Thus, the sensors need only small energy storage capacities to dampen energy fluctuations. (Kansal and Srivastava, 2003; Kansal et al., 2007; Chen et al., 2010; Tan and Panda, 2011).

J. Gummeson et al. (Gummeson et al., 2014) developed a small worn sensory device. This device is embedded inside a ring which limits the size available for energy storage. In their solution to this problem they used NFC to recharge the internal storage whenever the user reaches for an NFC-enabled smartphone. A similar approach can be used to operate larger devices. In the case of a smart sensor the energy storage can be made significantly larger, allowing for longer operation between the recharging occurs. At the same time larger antennas and more powerful NFC-readers can reduce the time needed for recharging the sensor. We also plan to use NFC to charge the sensor. In contrast to the work of Gummeson et al. we want to power a system that requires more energy.

A study from M. Rahimi et al. (Rahimi et al., 2003) investigates the feasibility of mobile nodes in order to provide energy to a sensor network. In this study the authors show promising results of their prototypical tests. This work focuses on the mechanisms for searching for energy in an environment and how the robots split the servicing (charging) of the sensor nodes. They focus their research on quantifying the power consumption of the network and specifying if the network is sustainable.
In contrast to this research we focus on the combination of energy transfer to the sensor nodes and the simultaneous data collection performed by mobile nodes.

Chen et al. (Chen et al., 2010) proposed and demonstrated a nearly self sustaining micro sensor that uses solar cells to generate the needed energy for sensing capacitance and temperature . This approach to build a self-sustaining sensor network seems promising but induces the need that the sensors are subject to a sufficient light source which might not be given in many scenarios. The work of Kansal et al. (Kansal et al., 2007) described power management techniques that can be used and they described how such mechanism can be implemented with respect to a known model of the desired energy source. That can be used to improve the work of Chen et al. (Chen et al., 2010). Additionally, such a model can be used in the proposed model to optimize the sensor usage.

In this paper we try to use NFC as communication technique to transmit data between a sensor and a mobile node. In this approach a robot is acting as the mobile node. This robot creates the connection to the infrastructure, thus acting as a slow and random link. The use of NFC furthermore allows us to transmit power to the sensor supporting it for high power operations and keeping it operational.

2.2 Energy Usage Estimation

The estimation of the energy consumption of sensors is an ongoing research. There are approaches to minimize the energy consumption of sensor nodes based on their specific energy levels and that take into account the energy levels of the surrounding nodes (Yan et al., 2013).

Other researchers such as Halgamuge et al. (Halgamuge et al., 2009) generated a model of a sensor's behaviour and try to estimate the energy consumption of the sensor based on the information of the behaviour.

To get better results than pure estimation of the energy consumption, we decided to create a research prototype of a low-power sensor on which the energy consumption can be measured.

2.3 Mobile Communication Partners

The idea of using mobile nodes in order to connect a wide spread sensor network has been explored widely in the existing literature. Most of these solutions use erratic moving partners (such as animals in their habitat who are equipped with a sensor node) to try to connect all of the stationary nodes(Shah et al., 2003; Ulz et al., 2017a; Rahimi et al., 2003).

The approach developed by Ulz et al. (Ulz et al., 2017a) to connect industrial machines using robots as links can be used to calculate the sensor node that should be visited next.

In the work of Shah et. al. (Shah et al., 2003) a multi-layer network with mobile nodes to connect sensors with each other and with the data sinks was proposed and explained. One of their main goals was to minimize the sensors memory to decrease energy demand. In their studies they proposed to mount the mobile nodes on animals, roaming through their habitat. In their assumption the mobile nodes (MULEs) are performing a random walk and stumble upon the sensors is not applicable to our use case. With that we can simplify many of the calculations done in order to get a reasonable memory size. Furthermore, as the mobile partner can directly communicate with the sensor, the sensor can suggest a return time for the mobile partner to improve memory usage and sensor lifetime.

Rahimi et. al. (Rahimi et al., 2003) describe an approach for energy harvesting and distributing the energy in a wireless sensor network (WSN) with the help of mobile autonomous robots. In their approach the robot moves through the observed area and finds a spot with enough available solar energy to charge the battery. The robot then moves towards the sensor nodes which need the energy and charges them. With this approach also sensors that can not harvest enough energy to sustain themselves can be operated using the delivered energy. This approach furthermore increases the lifespan of the rest of the sensors as they are provided with more energy than they could harvest on their own. In our approach the sensors are not only sustained by the mobile robot, but also their data is collected. This cuts the energy demand for transmitting the gathered data, allowing the sensors to operate longer.

In our presented approach we use controllable means of transportation in order to efficiently collect all gathered data, update configurations of the sensors, and charge the batteries. This controlled data collection can also provide means to predict the arrival of new data and the possibility to have information on the timeliness of the data.

3 Approach

Many systems, designed to be used as a sensor for a sensor network, use batteries, wired electrical connections, or continuous energy harvesting methods as their main power source. To utilize short bursts of energy as power source, the energy must be received and the excess must be stored in a usable manner. To do this, the energy is stored using accumulators or capacities. As we try to combine the transport of data and the delivery of energy, NFC technology, and thus energy bursts, are examined.

To use NFC as means of energy transport, the circuitry of the smart sensor must allow the extraction of excess energy of the NFC field. Furthermore, the excess energy must be directed to charge either a capacitor or an accumulator. This is done by extracting electrical energy from the electromagnetic field. The generated AC (alternating current) voltage is then rectified and the voltage and current are controlled to protect the sensor. To be more efficient, the circuitry can include means of distinguishing between operating the sensor from the stored energy and operating it from the NFC field and storing the excess energy. This switching of operation mode can be performed by the sensor's main controller.

To store the energy different solutions can be used. For this domain the most useful solutions are accumulators or capacitors. The energy density of capacitors is lower in comparison to accumulators. This means that capacitors can hold less energy. In contrast to that the power density of capacitors is larger. This allows capacitors to store and draw energy faster than equally sized accumulators (Zhang et al., 2013).

We decided to use a super-capacitor based development board as basis for the research prototype measuring the energy provisioning system (henceforth Prototype A).In addition to the prototype to measure the energy provisioning system, we created a research prototype on which the energy consumption of the sensor components can be measured (henceforth prototype B).

Using these research prototypes, we gather data to set up simulations that can represent the interactions between the sensors and the mobile agents, as well as help in gathering data to optimize the agent's visiting schedule. Here a simulation approach by Pieber et al. (Pieber et al., 2017a; Pieber et al., 2017b) can be used to connect the simulation of a smart sensor system to a simulation that is more capable of simulating the interaction between an agent and the sensor.

3.1 Research Prototypes

3.1.1 Prototype Overview

An MSP430FR5969 development board (TI, 2014) is chosen as a basis for prototype A. This board includes a super-capacitor as energy source, a microcontroller tailored for low power use, and a temperature sensor. It is then extended with a custom made PCB to connect an NFC interface (ams AG, 2006), capable of handing energy to the host system. The extension PCB can be configured using jumpers to allow different communication channels. This PCB furthermore features a simple power management system that limits the power that can reach the super-capacitor and can switch between the available power sources such that the capacitor can be charged when an NFC field is present. A circuit plan of the prototypical PCB is shown in Figure 1.

Prototype B consists of three parts. The *Energy Measurement Unit* (EMU, Testbench), a control computer, and the *Smart Sensor* itself. As basis for the EMU another PCB was designed. This is fitted to an MSP340FR5969 board that gathers the data and acts as a bridge between the measurement unit and the control computer.
The smart sensor consists of a microcontroller, interface ports, additional memory, an NFC interface, and a security co-processor. Each of these components is supplied by an energy channel coming from the measuring testbench. Additionally, most components can be cut from the power supply to reduce the energy demand of the sensor.
The testbench is controlled by a LabVIEW computer simulating the energy provisioning system. This is done by reading the energy demand of the sensor and setting the supply voltage according to the capabilities of the simulated provisioning system. In addition to the supply voltage the LabVIEW script also sets the digital potentiometers to adapt the gain of the current sensors. Using the information about the current drawn by the sensor components and the voltage of the system, an energy profile can be created that can be used to create simulations describing similar sensors. The design for prototype B is shown in Figure 2.

3.1.2 Prototype Details

When the NFC antenna of prototype A is subjected to an NFC field, a DC (direct current) voltage is generated. This voltage is represented as *NFC DC* in Figure 1. If this voltage is larger than the voltage at the capacitor *C* connected to *CHARGE+* the controller switches the analog-switch connected to *GPIO* such that the capacitor is connected to the voltage source via the resistor (*723* Ω). This controls the current that can pass through the capacitor. If the voltage difference between *CHARGE+* and *VCC* is smaller than a threshold, the switch is flipped and the resistor is short-circuited. This leaves the capacitor connected to *VCC* via the Schottky diode *D*. With this the current can not flow to the capacitor and it will not be charged any more. If the voltage of *NFC DC* is smaller than the voltage of the capacitor at *VCC*, the controller is powered from the capacitor. Should the voltage at *VCC* drop below a threshold, the controller switches in a low-power mode and waits for a voltage increase at *VCC* to start the charging again.
The voltages and currents that are present in the system can be measured at the jumper pins on the PCB. The most interesting values are the voltage at the capacitor, the voltage that reaches the sensor and the current that is drawn by the sensor.

The three parts of Prototype B are shown in Figure 2. The *Smart Sensor*, the *Testbench*, and the *Computer/Control* are represented as the boxes that combine the necessary elements.
The *Control* is located at a LabVIEW computer. This computer receives the measurements of the testbench

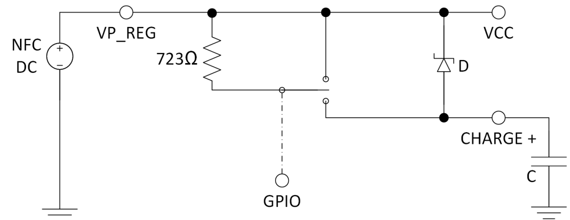

Figure 1: Circuit of the energy provisioning system of prototype A.

and sets the control signals for the testbench such that a specified energy provisioning behaviour is reached. The *Testbench* receives these signals and controls the variable voltage source and the digital potentiometers according to the control signals. It furthermore relays the measurement values of the current sensors to the *Control* computer. The *Testbench* has seven variable gain current sensors that can be used to observe the behaviour of the device under test.

The device under test - in this case the *Smart Sensor* - consists of six components, and therefore uses six measurement channels. The control unit of the sensor is an *Ambiq Micro Appollo 2 MCU*. This controller is connected via an I^2C bus to an *Optiga Trust X Security Co-Processor*. Another separate I^2C bus connects to an additional *FRAM* module as well as to an *NFC Interface*. Additionally, two *External Ports* are connected via IO pins. At these interfaces, different expansion modules can be connected. Using the IO pins, I^2C or *SPI* buses can be simulated to communicate with sensors, actuators, or other controllers.

Using *Load Switches*, the controller is able to cut different components off the energy supply to reduce the energy demand of the smart sensor as far as possible. This setup allows the measurement of the energy demand of each component of a smart sensor in a flexible way.

3.2 Simulation

The data generated from the prototypes is fed into simulations describing similar sensor systems. These simulations are necessary, as we are interested in the behaviour of the sensor in combination with different systems.

To get a more abstract system description of a smart sensor the gathered data needs to be generalized. Thus deviations in the results of the simulations from the measurements are expected.

To describe the sensor system electrically, a simulation using a SPICE program is created that represents the smart sensor. Here simplified but usable parameters can be extracted that are used in the calculations for the energy consumption of the smart sensor.

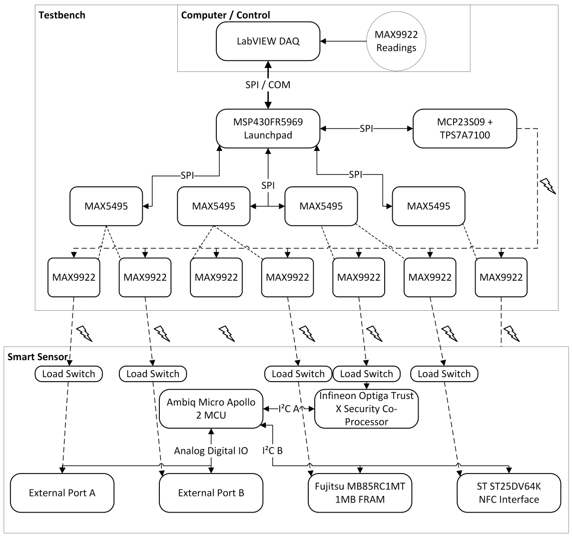

Figure 2: Design of prototype B.

The gathered parameters are then used to describe the electrical behaviour of the sensor is subsequent simulations.

The simulation of the sensor itself is written in SystemC as it allows the description of the entire system at different levels of abstraction. This is especially useful as the accurate simulation of a complex system impedes the simulation performance. This is counteracted by performing simulations on a more abstract level.

The environment is simulated using the Gazebo simulator, a simulation tool commonly used for robotic purposes. These two simulations are connected using a method developed by Pieber et al. (Pieber et al., 2017a). In Figure 3 such a simulation run can be seen. The robot interacts with the sensor, charging it, collecting data, and possibly reconfiguring it to alter the sensors behaviour. Using this simulation technique, the sensor simulation gets the stimuli from the environment and reacts according to it. This allows the quick creation of new test cases and stimuli, as well as the automatic evaluation of sensor responses.

Within the Gazebo environment, it is possible to align the antennas in various orientations to each other. Additionally, it is possible to introduce extra noise (such as noise from nearby communications or multi-path signal propagation) to the communication. This allows to find the answers to the questions asked in Section 1.

Summarized, this means that the measurements of the prototypes are used to generate a SPICE simulation. Parameters are extracted from this simulation that can be used to describe the electrical behaviour of the sensor. This description is done in SystemC. To

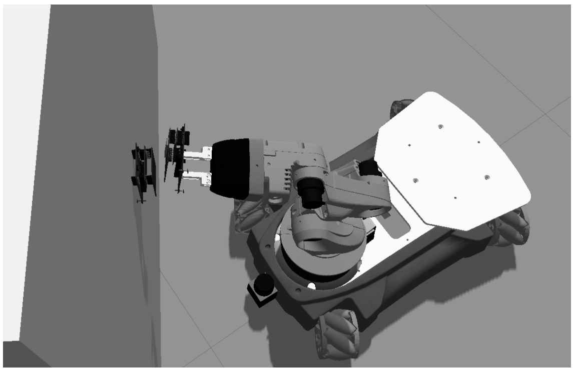

Figure 3: Simulation of an interaction between robot and sensor.

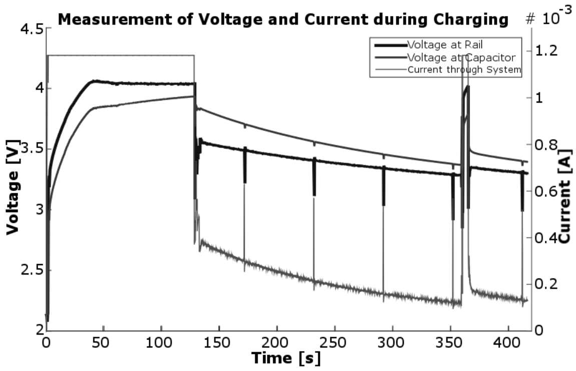

Figure 4: Measurement of the charging of prototype A.

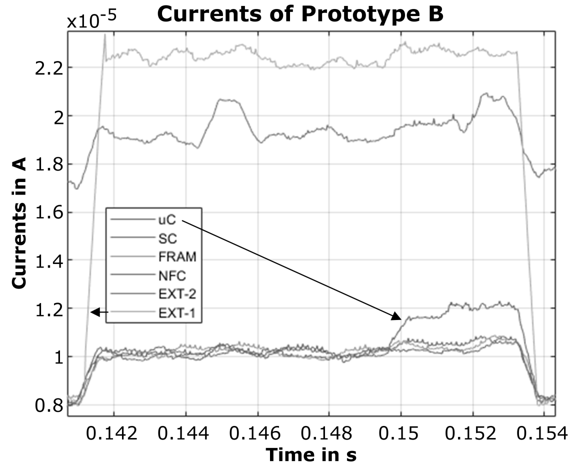

Figure 5: Current flow during measurements at prototype B.

subject the SystemC simulation to stimuli, the Gazebo simulator is used. This is done in order to quickly change the alignment of the NFC antennas and to introduce additional noise to the system.

This simulation yields data about the interaction of the smart sensor with the environment in different situations. Furthermore, information about the energy usage during operation as well as information about the memory usage of the stored values are created. This information, in connection with information about the type of generated data, can then be used by a mobile node to calculate the need to visit the sensor node to collect data and recharge it.
If multiple sensors are connected in this way, a sensor network is created using the robots as links between themselves and the infrastructure. This method was described by Ulz et al. (Ulz et al., 2017a) as a "Sneakernet on Wheels".

4 Measurements and Results

Prototype A is designed to measure the energy harvesting capabilities of the NFC connection. A typical measurement of this prototype can be seen in Figure 4. In this measurement the capacitor was charged for approximately 120 sec. During this time the voltage at the capacitor (middle line) reached the nominal voltage. After that the NFC field was switched off and the voltage at the rail (bold line) drops below the voltage at the capacitor. The current through the sensor (fine line) also drops significantly as the controller switches to a low-power mode. After that the controller awakes every 60 sec to take a measurement. At this times the current rises and the voltage at the rail drops as the capacitor and diode pose a resistance to the current. Again at 360 sec the NFC field is switched on briefly.

The operation of the smart sensor is measured using prototype B. In Figure 5 a sample measurement is shown. In this example the controller switches on an external sensor at port *EXT-1*. After that it waits until the sensor has initialized itself and starts the measurement. In this test the controller finally saves the gathered data and shuts down the sensor.
The microcontroller (*uC*) current rises at the start of the measurement as the sensor module starts its operation. During the communication with the sensor and the subsequent storing of the gathered values the power consumption and therefore the needed current rises further.
The continuous high current at *EXT2* is generated by other sensor hardware. Furthermore, the current usage by the Security Controller (*SC*), and the *FRAM* and *NFC* modules are increased at the start of the measurement routine.

Using the available data, a model can be created that shows the energy consumption of a generic smart sensor. Figure 6 shows the results of a simulation using the sensor model. In this simulation the charging behaviour of the sensor was simulated. This be-

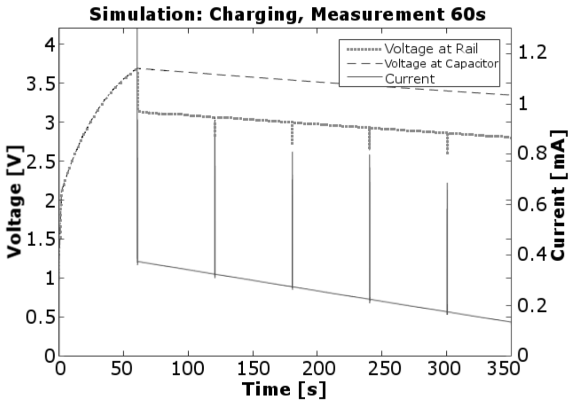

Figure 6: Simulation of the sensor charging.

haviour can be compared with the measurements of prototype A.

These results help in predicting the time it takes to charge one sensor using NFC energy harvesting and can furthermore help in estimating the time it needs to discharge the smart sensors energy storage.

In summary these results show that the charging of a smart sensor using NFC is possible. To charge the 0.5 F capacity approx. 2 minutes are needed. This also depends on external parameters such as the alignment of the antennas. The simulation of the sensor furthermore shows that the sensors operational time primarily depends on its duty cycle. While the sensor can be operated for approximately one day when performing measurements every hour, the lifetime is cut to about seven hours when measuring every minute.

5 Future Work

Using the prototypes we can perform measurements of security relevant operations. As prototype B also features a security coprocessor, we want to perform experiments determining the difference in energy usage during cryptographic operations. These experiments can show the requirements smart sensors and the energy provisioning systems need to fulfil to enable secured data handling. We are planning to take measurements of user authentication algorithms on smart sensors such as the one proposed by Pieber et al. (Pieber et al., 2017c), and testing data transmission protocols that secure the transmitted data using encryption and forward error correction such as the one proposed by Ulz et al. (Ulz et al., 2017b).

6 Conclusion

In this paper we showed the development of secured smart sensor platforms. Two prototypes are used to evaluate (1) the energy harvesting possibilities that arise when using NFC technology, and (2) the energy consumption of the main components of a smart sensor. These results are then used to implement simulations of the sensors. The simulations are able to not only simulate the smart sensor but also the environment. This is then used to answer crucial questions about the efficiency of the energy harvesting possibilities and the influence the environment has on the communication.

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