Hardware optimizations and solutions for wireless low power kinetic energy applications

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Preface

This thesis is written as part of a collaborative project carried out together with Emil Lenngren. The respective reports have a clear distinction between them and can be regarded as individual, stand-alone, reports. This particular report focuses on the hardware aspects of building low power, kinetic energy driven, peripherals, while Emil Lenngren’s report focuses on the software aspects of building efficient wireless protocols for such devices. The study of previous works and technologies is partially shared between the reports.
Abstract

The number of IoT (Internet of Things) devices available on the market has been growing rapidly in the past few years and is expected to grow even more in the years to come. These IoT devices are predominantly in the form of very small wireless peripherals with low power consumption making them suitable for running over extended periods of time using only coin cell batteries. In this degree project, conducted at Shortcut Labs AB, we investigate whether or not some of these devices could be suitable for being powered exclusively by kinetic energy without the need for any long term interim power storage, such as batteries or super capacitors. If this is possible it would not only remove the hassle of having to replace batteries at regular intervals, which is important if the devices are positioned at remote locations, but it could also help to reduce the amount of battery waste in the long run. For the sake of this project we have designed a hardware circuit that is able to communicate with other devices using a custom built protocol running on top of the Bluetooth Low Energy standard. This circuit does not require a battery and could potentially be used for many years without the need for any maintenance. To demonstrate this, the technology has successfully been applied to a concept product in the form of a dimmer wheel that can be used to change the brightness or color of Smart Home light bulbs. This is achieved by using a small electric motor as a generator in combination with an energy harvesting circuit in order to generate a stable voltage suitable for use with a wireless module.
Sammanfattning

Antalet uppkopplade IoT-enheter har ökat drastiskt de senaste åren och väntas fortsätta öka framöver. IoT, eller Sakernas Internet som det kallas på svenska, består övervägande av små trådlösa enheter med så pass låg strömförbrukning att de ofta kan drivas enbart av knappcellsbatterier. I detta examensarbete, utfört på Shortcut Labs AB, undersöker vi huruvida några av dessa enheter med fördel skulle kunna drivas uteslutande av rörelseenergi utan att kräva någon form av långtidsmellanlågning av denna energi, så som exempelvis i ett batteri eller en kondensator. Om detta var möjligt så skulle det innebära att man slipper byta batterier vid jämna mellanrum, vilket kan vara viktigt om enheten i fråga är otillgänglig placerat. Givetvis kan också onödigt batteriavfall undvikas, något som alltid är eftertraktat i branschen. I detta projekt så har vi designat och konstruerat en elektronikkrets som trådlöst kan kommunicera med andra enheter via ett skräddarsytt protokoll som är implementerat ovanpå Bluetooth Low Energystandarden. Denna krets kräver inget batteri och skulle potentiellt sett kunna operera under många år utan behov av underhåll. För att demonstrera detta så har tekniken applicerats på en konceptprodukt i form av en dimmer som kan användas för att ändra antingen ljusstyrkan eller färgen hos så kallade smarta lampor. Detta uppnås genom att använda en liten DC-motor kombinerad med en energiskördande krets som genererar en lämplig stabil spänning, vilket krävs för att kretsen skall kunna operera.
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1 Introduction

The concept of energy harvesting is not a new topic. What energy harvesting typically refers to is the process where energy from the surrounding environment is somehow harvested for either direct use or storage. The harvested energy most often, but not necessarily, originates from places where the energy otherwise would have been wasted. Energy harvesting is today used in many different fields with a wide variety of use cases. Typically the harvesting is applied when the energy sources are of very low density, but in the same concept applies regardless of the energy density. Take for example wind power plants that gather electricity by letting the wind turn propeller blades which in turn spin a turbine that can then generate electricity. Another example is solar power panels that convert the radiation energy from the sun into electricity that we can use. Both of these two are examples of very high power density applications. But as stated, it is worth mentioning that the latter two examples are not often referred to as energy harvesting systems due to their very high energy density and power output. The term Energy Harvesting has generally been accepted to only refer to the method of gathering and supplying energy for small, often wireless, low power electronics circuits, but, once again, the concepts are similar and can be applied to products regardless of the power consumption.

The main focus of this report is to look at energy harvesting solutions for the IoT, Internet of Things, industry in particular. This is a relatively new industry that has just started to grow and expand at a very rapid pace in the past few years. Many large companies, such as Ericsson, are focusing a lot of research into this new market segment. Ericsson themselves predict, and has set up a goal for themselves to achieve, that by year 2020 more than 50 billion devices will be connected to the IoT\textsuperscript{[1]}. The core problem with this is that no matter what kind of device we are talking about, they all have to be powered somehow. If the device happens to be directly connected to the main power grid then it is not a big problem. However, if the device is wireless, like a lot of devices are today, then it typically has to be powered by a battery. People nowadays are usually quite used to either having to charge the batteries in their different devices, or simply replace the non rechargeable ones at regular intervals. But imagine when you have perhaps 100 different devices around your house that all needs to have their batteries charged. This might quickly become a cumbersome scenario to maintain. This brings up the need to let as many of these IoT devices as possible to not only be self-powered by the environment, but also maintenance-free.
Since the topic of energy harvesting has been around for a long time it is not a surprise that it has been researched in this field of study as well. Wireless Sensor Networks, WSNs, for example have for many years been using energy harvesting to power sensors where conventional power sources are not available. A WSN is a communication infrastructure used in different industries for monitoring conditions at different, often remote and inaccessible, locations. Such networks are today being used for many different purposes, with applications ranging from structural monitoring of buildings\cite{2} to data gathering for volcano research\cite{3}. There are a great variety of parameters that can be monitored by a WSN, some examples being temperature, humidity, pressure, wind direction, wind speed, etc.

While WSNs are not typically considered to be part of the IoT industry, they still share a lot in terms of how the peripherals, or nodes, are constructed, which is why it is important to study them in this report as well. Much of the study and research that has been made around WSN nodes can be directly applicable to a few different kinds of IoT peripherals. More importantly, though, is that most of the research made surrounding energy harvesting for WSNs up to this point has almost exclusively looked at solutions where very small amounts of power can be harvested during long periods of time, which is an important distinction to the main focus of this report. For those kinds of applications it is assumed that the system has to be completely autonomous, meaning that they have to operate completely without any input of a human.

2 Thesis objective

This thesis investigates if the concept of energy harvesting is applicable to applications using just-in-time energy generation without long term interim storage for wireless peripherals. This is determined by attempting to design and implement a working hardware and software concept where the core technology could be turned into a consumer product for mass production.

The conceptual product constructed is a wireless ”dimmer knob” that can be used for the purpose of adjusting either the brightness or color hue of smart home light bulbs. This was chosen both because it is a good use case that could have a real world value, but it is also provides a perfect example of an application where you actually have kinetic energy present due to the nature of such a product. If implemented properly, that energy could be harvested without actually changing the interaction with the product from a user’s point of view.
2.1 Delimitations

It will not be included in the scope of this thesis to look at, or consider, aspects regarding industrial design or other design elements, such as size and format. Those aspects are left to whoever wishes to build something on top of this technology in the future. This way, this work can focus more on the technical parts without being limited by external factors.

There are many different energy sources commonly used with energy harvesting, but only the ones that are closely related to this work will be studied. Other sources, such as wind, radiation, or even bio-fuel cells (blood sugar oxidation)\[6\], will not be considered in the scope of this work.

3 Existing harvesting technologies

Low power wireless peripherals typically operate at average power levels of around 1-10µW, with peak levels during radio transfer in the area of a few mW. This is important since these power levels are on the borderline of the power that can actually be harvested from the surroundings within a reasonable amount of time. Three categories of power sources are by far the most widely used and thus worth mentioning in this work. These three are thermal (TEC, TEG, Thermoelectric), vibration (Piezo) and photo voltaic (Solar)\[4\]. These sources, if adapted and implemented properly, provide good enough energy density for conversion to a regulated voltage in order to charge batteries and super capacitor storage elements.

3.1 Thermoelectric harvesting

Thermoelectric generators are solid-state energy converters whose combination of thermal, electrical, and semiconducting properties allows them to be used to convert waste heat into electricity\[5\]. This process, often called the Seebeck effect after its discoverer Thomas Seebeck, occurs when a thermal gradient is formed between two dissimilar conductors which results in heat flow and diffusion of charge carriers that ultimately produces a voltage. These thermoelectric generators used in energy harvesting for wireless sensors can only produce a very low voltage in the area of 10-500mV depending on the temperature difference and the size of the element. This means that a step-up voltage transformer is needed.

Converting a very low voltage to a regulated voltage, say 3V, consumes a lot of current. This is not very ideal since thermoelectric generators usually do not produce high current either, unless a very large temperature difference can be achieved. Average harvested power levels can reach 10-30 µW/cm\(^2\) for ambient conditions, with the main
affecting parameter being the achieved temperature difference\(^9\). These figures are not quite high enough to continuously power wireless sensors, especially since they are best case values and do not account for temperature changes during the day. This means that the only option is to use some sort of interim storage, such as a battery or super capacitor, to build up a sufficient charge over a long period of time. In practice this would mean that a sensor using this technology would have to spend a relatively long time to build up a charge, to then only be able to transmit a few wireless data packets.

While this may sound like a confined technology with limited use cases, the reality is that it actually is sufficient for many use cases where an occasional data transmission is all you need. Consider for example a sensor that measures and transmits the temperature at a location once a day. In this case this approach may very well be a good solution, especially if solar panels cannot be used for some reason, such as if the sensor is positioned in a dark location.

3.2 Piezoelectric harvesting

Piezoelectric harvesting makes use of the so called Piezoelectric effect that occurs when there is an electromechanical interaction between the mechanical and electrical state in piezoelectric materials\(^7\). A piezoelectric charge is generated when a force is applied to those kinds of materials, where crystals and ceramics are the most widely used. What this means in practice is that when you apply a force to a piezoelectric element it will generate a voltage that is proportional to the size of the force. This also depends on the element that is being used, but some piezoelectric generators can achieve thousands of volts. In most cases you will not be able to draw much current. A side note is that the piezoelectric effect also works in the reversed direction, meaning that you can generate mechanical force by applying electricity. This is in short how piezo crystal clocks works, such as those used in most electronics today in order to generate a reference frequency for processors.

Even though this technology was studied and demonstrated during the mid 1800s it actually took a very long time before the first real usages appeared. It wasn’t until the early 1900s that it got its first real field of application when the sonar was introduced. A piezoelectric element was used to detect the vibrations of sound waves. The voltage produced by the piezoelectric element was used only to detect the signals, and not to actually drive any of the equipment. In the late 1990s more research about piezoelectric energy harvesting started to surface. Perhaps the main reasons for this was that electronics were finally starting to get efficient enough to make use of this technology. One
of the earliest research papers about this came out from MIT in 1998\cite{8}. This research looked at the possibilities of integrating piezoelectric elements into shoes in order to produce electricity while walking. The conclusion though was that it both generated too little power and was too clunky to put in a regular shoe. They did, however, state that the technology could potentially be useful for small RF tags\cite{8}.

The average power level for piezoelectric generators is expected to be around $4 \mu\text{W/cm}^2$ for ambient conditions, putting it at even lower levels than what thermoelectric generators are capable of\cite{9}. It is clear that piezoelectric generators have potential in this field of study, but just like the thermoelectric generators, they are only able to produce very low power output. This means, once again, that interim storage is needed in order to build up a sufficient charge over a longer period of time. While this is sufficient for many use cases, it is not what we are looking for in this work.

### 3.3 Solar harvesting

Harvesting energy from light is without a doubt the most well known, and well used, method of energy harvesting. This technology has been used in many different products during the last decades ranging from small pocket calculators all the way up to full-blown power plants. A solar cell is, in principle, a simple semiconductor device that converts light into electric energy by making use of the **Photovoltaic effect**. This effect is both a physical and chemical phenomenon that, in short, occurs when the energy of the colliding light rays are absorbed by the electrons in the surface of the exposed material\cite{11}.

This technology has higher possible energy density than both thermoelectric generators and piezoelectric generators. Average harvested levels are around $10 \mu\text{W/cm}^2$ for indoor ambient light and $10 \text{mW/cm}^2$ for outdoor ambient light, but it can be up to 5 times larger than that in peak sunlight\cite{9,10}. This method also has the advantage of being easily scalable, meaning that you can add more solar cell surface area without too much cost in case you need more power. The very obvious drawback with this is that as soon as you don’t have any light you will no longer harvest any energy. For a wireless sensor to work with this kind of setup you would have to make sure that it can harvest enough power during the light hours of the day so that it can still function when it is dark, such as during the night. This is perfectly fine for most use cases and you should be able to fine tune your electronics design so that you don’t have to worry about down time due to power outage. However, this still means that we have to have long term interim storage, which does not meet the requirements of on-demand harvesting that we are looking for in this work.
3.4 Electromagnetic induction harvesting

Electromagnetic induction is by far the most widely used method of generating electricity. This method was first discovered in the early 1800s by Michael Faraday and has since been used in countless applications. The principle of electromagnetic induction is quite simple and is explained in Michael Faraday’s famous law of electromagnetic induction, which states: “that a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux”. What this means, in more simple terms, is that electromagnetic induction is the process of using magnetic fields to produce power. This is the fundamental aspect that has laid the foundation for many products such as electrical generators, electrical motors, transformers, inductors, etc.

While it is obvious that you can generate electricity with an electric generator, the problem in this case really lies in finding a solution that is suitable for energy harvesting. You have to make sure that it is both reliable enough and compact enough in order to put them inside small peripherals. A common problem is that most electric generators generate electricity in very broad voltage ranges depending on the RPM (Revolutions Per Minute). Anywhere between 0V up to 30V is common, but such high voltages can cause damage to many components.

However, the major reason for why this has not been researched much in this context is that you only can generate electricity when you have kinetic energy. Since virtually all IoT devices today, as previously mentioned, are mostly autonomous it might be hard to find enough kinetic energy in order to drive the generator. We believe that many use cases will arise in the upcoming years where you have devices that have some sort of user interaction suitable for kinetic energy harvested. It could for example be a door knob that automatically transmits its status when it is turned, or an office chair that transmits some data whenever the user sitting on it is rotating the seat. There are endless possibilities, but the one that we are investigating in this work is if you can do a light dimmer switch, or a volume knob, that uses the rotation caused by the user in order to generate the power needed to send the data.

4 Wireless data transfer

To send data wirelessly from one device to another, a predetermined protocol must be used in order for the two devices to understand each other. This can can be achieved by using one of the standard protocols available on the market.
4.1 Bluetooth Low Energy

Bluetooth Low Energy (BLE) was released in 2010 as part of the new Bluetooth 4.0 specification\textsuperscript{[13]}. Its intention is to become a standard protocol for wireless transfer of small data for low power wearables. At the time of writing, this is the standard used in most of smartphones produced. The previous Bluetooth standard, now referred to as "classic" Bluetooth, was designed to stream data at a relatively high bit rate, making it suitable for file transfer and audio streaming. BLE on the other hand is designed to be an energy efficient protocol for applications where a low bit rate is sufficient. This is most often used for the purpose of exchanging data between a host device, such as a smartphone, and one or more small peripherals such as temperature sensors, heart rate monitors, fitness trackers and so on. Since those kind of peripherals are typically battery driven and due to the fact that the amounts of information needed to exchange are often quite small, BLE is optimized to be lower power than classic Bluetooth – hence the name.

In the BLE standard there are two kinds of devices, centrals and peripherals. Peripherals advertise their presence and are connectable. Centrals scan for peripherals and initiate connections to peripherals. Normally a smartphone would take the central role where a user for example can scan for peripherals and connect on demand using the phone’s interface. To be able to use very low amounts of energy on average, the protocol is designed so that the devices can be in sleep mode as much as possible, which means in practice consuming almost no energy at all. Only at specific synchronization points must they turn the radio on to exchange data packets and then subsequently go back to sleep immediately afterwards.

There are two different operating states a peripheral can be in: the advertising state or the connected state. When advertising, it broadcasts a packet containing at most 31 bytes on three different radio channels at regular intervals. A central can be in three different operating states: scanning, initiating or connected state. When scanning, it periodically has the radio powered on and periodically powered off depending on how much energy you are willing to consume. If it has the radio on while a peripheral is sending an advertisement packet, that packet will be read. The advertisement packet will not be read if the radio is off at that time. The initiating state works the same way as the scanning state, with the difference that it may respond to an advertisement packet with a connection request. After the peripheral send out its advertisement packet, it listens for a short time for incoming connection requests. If a connection request arrives, a connection is established. From that time, the central and the peripheral have their clocks synchronized and will continue to exchange packets with a specified interval.
For our application we have to maximize the probability of the data arriving on the other end before the peripheral runs out of power. The best way to do this, presumably, is to just advertise the data and let the other side scan. On the contrary, if a connection had to be established first, it would require more work to be done which of course takes more time. However, the upside of doing that is that it allows for the peripheral to be sure that the data has been retrieved since all packets are acknowledged in connected state. Establishing a connection also means the BLE standard’s security (encryption and authentication) can be enabled.

4.2 Other protocols

There exists other protocol such as ANT and Zigbee. These protocols will not be considered in this thesis since implementations of those protocols are, at the time of writing, not as broadly available as BLE is. BLE is nowadays supported in all new smartphones, tablets and computers while other technologies need separate equipment to communicate with such devices. Another reason is simply that these protocols have very similar power characteristics so most of the aspects in this report would apply to a product regardless of the underlying protocol being used. When deciding on a protocol it will depend most on what kind of devices you wish to communicate with and what protocols those particular devices support.

5 Hardware

When constructing a product that has to keep the current consumption to an absolute minimum, it is very important to put a lot of consideration into how the hardware should be constructed. In this project, the two most important components to consider is the energy harvesting circuit and the wireless communication circuit. A previous work on energy harvesting combined with BLE suggests the following figures in regards to the wireless communication\(^\text{[12]}\):

- Energy consumption for a connection setup: 0.3 mJ
- Energy consumption for a data transmission with a notification packet: 0.13 mJ
- Energy consumption for single data transmission if the transceiver is switched on/off between the data transmission: 0.78 mJ

This study was done in 2012 and since that time most new Bluetooth controllers have optimized energy consumption. This, in combination with our further optimizations,
leads us to believe that we should be able to achieve lower energy consumption than that.

5.1 Microcontroller (IC)

Since the very first release of the BLE specification in 2010 a vast number of companies has launched their own BLE IC’s. Texas instruments, Dialog Semiconductor, Nordic Semiconductor, Broadcom, Atmel and Toshiba are some of them, all with the aim of operating around 10µW average power consumption, depending on the duty cycle of course. At this point in time it does not matter much which chip you use since they all compare well with each other in terms of energy consumption. Depending on your needs there are some that have built in Flash storage, EEPROM storage, or, for the budget conscious, OTP (One Time Programmable) memory.

Since most applications today run off of battery sources then the main focus with these IC’s has always been on optimizing the continuous sleep mode current. On battery powered devices the relative time that is spent in the booting sequence is negligible since those devices typically only boot just a few times throughout their lifetimes. Once a chip is booted it spends the majority of the time in so called sleep mode with the program code stored in RAM, allowing for quick wake-up and code execution. The point here being that after the chip has booted the power consumption is so small that it justifies having it in sleep mode for the rest of the time. This, however, would not be possible for an application where no battery is present at all, such as with the solution proposed in this work. This energy harvesting approach only works when the selected power source is producing the energy, so in order to achieve the desirable result we need to optimize and rework the booting sequence in order to adapt it better for the said use-cases. It is due to this requirement that we choose to go with OTP memory for this project since OTP is much faster and energy efficient to read from upon a cold boot as opposed to Flash or EEPROM.

After our initial research we decided to move further with the DA14580 chip from Dialog Semiconductor due to its minimalistic approach and good overall power characteristics. The DA14580 is a fully integrated system on chip (SoC) design containing a 16MHz 32 bit ARM Cortex M0 processor, 42 kB SRAM, 8kB Retention RAM, 32 kB OTP, 84 kB ROM, as well as a Bluetooth radio transceiver, all in a 2.5 mm x 2.5 WLCSP package. An overview of this can be seen as a block diagram in Figure 1.
5.2 Harvesting circuits

People have for a long time tried to construct circuits for energy harvesting applications. Historically however, these circuits have resulted in very complex discrete circuits with upwards of 30 components and yet still struggled to provide high enough efficiency to be of practical use\(^{[10]}\). It will almost exclusively be less efficient to construct a circuit on your own by gathering a set of components and adding them to your design, rather than using an Integrated Circuit that already has those components internally. This is true not only for power consumption, but also for product size and total component costs. Integrated circuits are used in virtually all electronic equipment today and is in major part responsible for the vast technology improvements that we have seen over the last half century.

With the decreasing power consumption of wireless technologies, and thus the increasing possibilities of energy harvesting for it, it was just a matter of time before the large chip manufacturers started to put research into energy harvesting Integrated Circuits. Sure enough, in the recent years many new harvesting IC’s has surfaced from well known manufacturers such as, but not limited to, Texas Instruments, Linear Technologies, Maxim Integrated and Cymbet Corporation. All of these solutions, while having their slight
differences, essentially solves the same problem, which is to efficiently convert an unsta-
ble or variable voltage into a regulated voltage to charge a battery or super capacitor. 
This could be either step-up conversion or step-down conversion depending on the input, 
which can vary in the span of only a few millivolts all the way up to hundreds of volts. 
Depending on the configuration some of them also have an internal bridge rectifier in 
order to support reversed polarity, which is needed for example in the case of a piezo-
electric generator since it generates an alternating current.

When choosing the specific energy harvesting IC to be used in this project we researched 
what was available on the market and then choose the one that best seemed to fit with 
our demands, the Linear Technology LCT3588-1. This subsequently resulted in us doing 
more research about this particular product and Linear Technology as well.

The LTC3588-1 offers a complete energy harvesting solution that is optimized for high 
output impedance energy sources such as piezoelectric, solar, or magnetic transducers. 
It can handle input voltages in the range of 2.7V to 18V and can provide up to 100mA 
of continuous output current, which is well above our needs. Furthermore, it does have 
a full rectifier bridge, as can be seen in the block diagram in Figure 2, for the two inputs 
PZ1 and PZ2. These inputs, as you may have guessed by their names, is aimed at han-
dling the alternating currents from piezoelectric generators. However, this can be used 
for other purposes as well and it turns out to be quite suitable for an electric generator 
as well since it can produce currents in both directions depending on which way it is 
turned. Four selectable output voltages 1.8V, 2.5V, 3.3V and 3.6V can be configured 
with the external bit pins D0 and D1.
6 Software

In order to make use of the hardware, a customized software is needed. This software runs directly on the microcontroller and is often referred to as embedded software due to its low level characteristics.

6.1 ARM Cortex

The ARM Cortex-M0 processor is used in most Bluetooth chips due to its performance and low cost. On the DA14580, the processor consumes around 0.45 mA when it is active. It uses the ARM Thumb-2 instruction set which is known to make the compiled code compact. This has several benefits. The first is that the amount of RAM required to hold it can be minimized. With less need for memory, lower power consumption can be achieved. The second is that it will be faster to load code from persistent memory into RAM, shortening the boot time.
6.2 Bluetooth stack

All Bluetooth controllers are supplied with a Bluetooth software stack that acts as an interface between the Bluetooth hardware (radio receiver and transmitter) and the application software. The stack is structured in many layers. For a connected device, we have from the bottom to the top radio / physical layer, Link Layer, Logical Link Control and Adaptation Protocol (L2CAP), GATT. There is also a GAP layer that is mostly a wrapper layer around the link layer that is used to establish connections, scanning and advertisements. If security is wanted, there is a layer called SMP (Security Manager Protocol) that runs on top of L2CAP. The SMP manages the pairing sequence that is used to initiate encryption. An illustrative of the stack can be seen in Figure 3. For a peripheral that only advertises the only involved layers are the Physical layer, Link Layer and GAP.

![BLE stack - layers](image)

Fig 3. BLE stack - layers

6.3 Application

The actual application that wants to send or receive data runs on top of the Bluetooth stack. An application that uses BLE on an embedded system usually collects data from sensors and might interact with a user through peripherals such as buttons and LEDs (Light Emitting Diodes). The application does all the logic talking to the external I/O ports and uses the GAP and GATT interfaces to interact with remote devices over BLE, meaning that the application developer doesn’t need to know about the lower layers.
7 Methodology

After the initial research of the related technologies it was clear that a custom hardware and software solution had to be designed and implemented. For the hardware side it was essential that the design was highly energy conservative and efficient as to not waste any energy. The software side had similar requirements, which was to get as much work done in as little time as possible. This essentially boiled down to making sure that no unnecessary instructions were performed and that the cold booting time was kept at a minimum.

Since the desired result of this work is to achieve a solution that is usable and applicable in real world scenarios, it was essential that a series of realistic tests were performed. These tests, which are described in more details in the Measurements setup part of the Results section, were performed in part to validate that the design was working as hoped, but also allowed for alternation of the variable parts of the design in order to better find the optimal solution for this particular setup.

For this work, as mentioned earlier, it was decided that the product to be constructed should be in the form of a combined wireless dimmer and color wheel for home automation smart lights. This was decided because it provided a good real world use case that is easy to relate to.

For the hardware itself one practical requirement and goal was set up:

• The energy harvesting aspect of the product should not interfere negatively with the user or significantly alter the user experience in any way.

The main reason for why this requirement was set up was because we believe that the user should not have to make any sacrifices or get a lesser user experience simply because the product is run by kinetic energy. For this we came up with target values for the speed at which the knob had to be rotated, the amount of time it had to be rotated, as well as the maximum acceptable system latency.

When it comes to the speed aspect it was important that the user should not have to turn the knob too fast, but also not have to compensate with too much force at low RPM’s. What was decided to be acceptable here was decided after a series of user evaluations. Different speeds were tested on a handful of people and then the speed that the most people found acceptable was chosen. The conclusion was that our target should be that a user should not have to turn the knob any faster than 60 RPM and not any further than half a turn. At those specifications the wheel did have a slight and
noticeable rotational resistance, but not enough to make it hard to turn. This resulted in a good reference value to perform the tests at: a half turn in half a second.

Perhaps the most important aspect to keep in mind is the total system latency, meaning how long it takes from when the user starts to turn the knob until something actually happens to the light bulbs. The topic of response time in systems with user interaction is something that has been researched a lot in the past. For example, Jakob Nielsen’s book *Usability Engineering*\(^{14}\) touches on this topic and brings up a few good guideline values for different response times:

- **0.1 second** is about the limit for having the user feel that the system is reacting instantaneously, meaning that no special feedback is necessary except to display the result.

- **1.0 second** is about the limit for the user’s flow of thought to stay uninterrupted, even though the user will notice the delay. Normally, no special feedback is necessary during delays of more than 0.1 but less than 1.0 second, but the user does lose the feeling of operating directly on the data.

- **10 seconds** is about the limit for keeping the user’s attention focused on the dialogue. For longer delays, users will want to perform other tasks while waiting for the computer to finish, so they should be given feedback indicating when the computer expects to be done. Feedback during the delay is especially important if the response time is likely to be highly variable, since users will then not know what to expect.

These guidelines are sometimes referred to as the *Power of ten* rule. To summarize this we can say that anything below 100 ms will be experienced as an instantaneous reaction that is directly controlled by the user itself. Anything above that will make the user feel as if the system is not a live system and that some sort of processing is being made between the interaction and the event. This is not to say that a person can never notice a delay of less than 100 ms, but rather that they will not be bothered by it as it will not change the perceived experience. There are many scenarios where an input system with 100 ms latency would be rather useless, but that is not relevant in the scope of this report.

Due to this it was decided that the target for the maximum total system latency should be no more than 100 ms.
7.1 Hardware construction

This section describes how the hardware was created and which factors were considered while doing so. The hardware was also constructed in such a way that it could easily be tested and fine-tuned to achieve the most promising results. In particular, the circuitry was split into multiple sections to allow for different measurement setups.

7.1.1 Schematic design

Before the hardware could be constructed, it had to be designed on a schematic level. From the initial research, we knew that the hardware design would be centered around the DA14580 from Dialog Semiconductor as well as the LTC3588-1 from Linear Technology. After a few design iterations, we ended up with a design that seemed promising and the resulting schematic can be seen in Figure 4.

The schematic is divided into three standalone blocks:

- *Energy harvesting block*
- *Wireless block*
- *Variable energy storage block*

The *Energy harvesting block*, centered around the LTC3588-1, is responsible for converting the variable input voltage into a stable, near 3.3V, voltage whenever possible to be used by the wireless block in order to transmit the data. The two inputs, \( PZ_1 \) and \( PZ_2 \), will be tied up with the two poles, \( Gen_1 \) and \( Gen_2 \), of the electric generator. These two inputs are directly connected to either side of the internal rectifier bridge of the LTC3588-1, meaning that it will operate as expected regardless of the polarity of the inputs. The input \( V_{IN} \) is tied up with the rectified side of the two mentioned inputs. The final regulated voltage is tied up with the grid called \( V_{CC} \) in this schematic.

The *Wireless block*, centered around the DA14580, is responsible for all the wireless data transmission as well as all of the computational instructions of this design. This block can be seen as a stand-alone, fully functional, computer with an integrated radio transceiver and baseband processor for Bluetooth Low Energy. Alongside the DA14580, we can see, among others, a 16 MHz 10 ppm crystal as well as a PCB trace antenna. The \( V_{BAT3V} \) input of the DA14580 is directly tied up with the \( V_{CC} \) grid generated by the harvesting block. This essentially means that as soon as the harvesting block switches on the 3.3V voltage, the system will start its booting sequence. You can see in the schematic
that quite a few access points which were added for the purpose of making it easy to experiment with. The \textit{UART TX/RX} and \textit{VPP} were added to allow for \textit{OTP} (One Time Programmable) writing of the final application code. \textit{SWDIO} (Serial Wire Debug IO) and \textit{SWCLK} (Serial Wire Clock) are used for \textit{JTAG} compatibility which is handy since it means that the system can be hooked up to a debugger. \textit{SCL} (Serial clock), \textit{SDA} (Serial data) and \textit{WP} (Write Protect) were added to allow for future expansion and use of either EEPROM or Flash non-volatile external memory.

The \textit{Variable energy storage block} is a part of the energy harvesting block, but it was separated on the schematic for the purpose of making it more simple. The core purpose of the variable energy storage block is to allow for some experimental testing of different capacitance values. The \textit{CSTORAGE} capacitor is tied up directly to \textit{VIN} of the LTC3588-1 meaning that it operates directly on the input side of the chip. The final capacitance value will be derived from the final testing. The fact that this capacitor is connected to \textit{VIN} means that it will be directly charged by the generator which in turn means that it has to reach a certain input voltage threshold before the LTC3588-1 can start regulating. This is also why it is so important that this capacitor is properly sized. If it is too big then it will introduce a delay to the system, but if it is too small then we stand the risk of ending up with a setup that cannot produce a stable output voltage due to an insufficient input buffer.

As mentioned, the full schematic can be seen in \textit{Figure 4} and should provide a good starting point for other projects, and products, in the future.
7.1.2 Electric generator

To actually generate the electricity an electric generator was needed. When designing a consumer product this part of the design would be very important since there are multiple factors to take into consideration. Perhaps the most important factors here being size, cost and gear ratio. For a consumer product where compact size is needed then you would most probably want to custom build the generator to fit your needs. Since the purpose of this work is not to actually design a consumer ready product, but rather to prove the concept, it was more reasonable to use a standard component for this part.

The decision was made to use an off-the-shelf DC-motor from MicroMotors and run it in reverse to get the generator abilities. The particular model chosen is from the HL149 series and is rated at 12 VDC and up to 60 mA at 78 RPM output rotation without any load. It has a 43:1 gear ratio built in which is necessary since we want to spin up the motor as quickly as possible when the user turns the wheel. This was chosen in combination with a knob wheel with a 45 mm radius that, when paired up, would position us at a favorable voltage range for normal usage. An illustration of the selected part can be seen in Figure 5.

![DC Motor, 12 VDC HL149 43:1, Source: Mircomotors s.r.l](image)

Admittedly, this setup is probably a bit more redundant than one would use in a final design, but for the purpose of testing it is better to start out with a high margin and then work your way down to an optimal design for the particular product being made. With these specs the generator should peak around 10-12V at a speed of 60 RPM (or 1 revolution per second) which is our target speed.
7.2 Software design

In one sense you could say that the software design, as a concept, for a product like this is a bit more straight-forward than the hardware design. When developing software with energy consumption in mind you typically have to consider the following two points:

- Minimize the total number of processor instructions and tasks that the system has to perform.
- Avoid the instructions and tasks that consume the most power.

In reality these two can be tricky to achieve at the same time and usually the optimal solution is somewhere in between the two. When the system is active running on the main 16 MHz clock the total continuous consumption averages around 0.4 mA. It is obvious that the less amount of time we can spend here and the more time we spend in sleep mode using the 32 KHz Low Power clock the better the overall consumption average will be. While this is important, the fact still remains that if you do not properly optimize the work that makes use of the antenna, then the rest of the consumption would be negligible anyway.

When the radio transmitter is active on this particular circuit it draws an average of 4.5 mA, regardless of the data sent. To send one bit of data takes per definition one microsecond, as defined in the Bluetooth specification\(^{[13]}\). This specification also states that all listening devices (Centrals) must listen on three specified Bluetooth channels sequentially. It is not a requirement that sending devices (Peripherals) also transmit to all of those three channels, but if they do not then it will on average take three times longer for the packets to be discovered. Since response time is critical for this application, using all three channels is appropriate in this case. With this information we can actually set up a formula for how much energy the data transmission itself will consume. Knowing that coulomb is the unit of electric charge which is defined as current multiplied by time and that the energy is calculated by electric charge times the voltage, we can derive the following formula:

\[
E = b \cdot 3 \cdot 0.0045 \cdot 3 \tag{1}
\]

where \(b\) is the number of bits to be transmitted. The result \(E\) will be in units of microjoules (\(\mu J\)). The multiplication by 3 at the end is the voltage 3V.
The data contents of an advertisement packet is split up in two different areas. The first area contains all the mandatory bits that are required in order for the protocol to actually be able to route the packet. The second area is the actual user data itself, also often referred to as the payload, which is simply the data that we actually want to transmit. Table 1 below lists the mandatory parts of the advertisement packet.

<table>
<thead>
<tr>
<th>Field</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamble</td>
<td>1 byte</td>
</tr>
<tr>
<td>Access address</td>
<td>4 bytes</td>
</tr>
<tr>
<td>Header</td>
<td>2 bytes</td>
</tr>
<tr>
<td>Bluetooth address</td>
<td>6 bytes</td>
</tr>
<tr>
<td>CRC</td>
<td>3 bytes</td>
</tr>
</tbody>
</table>

Table 1. - Mandatory data in an advertisement packet

With this information it is easy to see that the absolute minimum size of an advertisement packet that can be sent is 16 bytes and that is achieved only when we have no payload at all. If we take these 16 bytes (128 bits) and insert that into the formula derived earlier we get 5.53 uJ, or 0.00553 mJ, which is the absolute minimum benchmark value for one packet.

Figure 6 shows the current measurements and accumulated charge of one advertisement packet where 31 bytes of payload was used. 31 bytes of payload results in a total amount of 47 bytes, or 376 bits, including the header. Using \( b=376 \) in same formula once again gives us a theoretical optimal value of 0.0152 mJ for this particular transmission sequence. In the figure, however, we can easily deduce that this theoretical optimal, while being a good benchmark value, is actually not very accurate since the consumption in practice will exceed that quite a bit. This is due to the fact that we have build-up and switching times before and in-between the three channels, which run at different frequencies, where the processor is busy doing other tasks than actually transmitting data. This behavior can be seen in Figure 6 where the actual data transmission only happen on the flat areas on top of the three pillars. Reading out the charge over those periods it we can derive that roughly 0.0159 mJ is consumed during transmission, which is very close to the theoretical value. Unfortunately the system consumes about 0.027 mJ over the whole time period due to the mentioned overhead tasks.

To refer back to what was discussed in regards to system tasks of different power char-
acteristics, the point here was that you need to know which parts of the system that are actually worth optimizing. To send one advertisement packet, taking into account only the data transmission itself, would consume the same amount of energy as the rest of the system would if the processor was running at full speed for 3.6 milliseconds. Given that our processor runs at 16 MHz that in theory means that performing 57600 processor instructions consumes the same amount of energy as it would transmitting 128 bits of data. So essentially, trimming off a few bits of your data protocol could have a significant impact on your overall power consumption.

Fig 6. Advertisement packet with 48 bytes of data sent on three channels

These aspects, among others, were considered when designing both the chip software, as well as the wireless data protocol. The collaboratory work of Emil Lenngren goes into great detail on how an efficient software implementation for a product like this should be constructed.
8 Results

The results of this report were gathered using two different measurement setups, as mentioned previously. The first setup only considers the the energy harvesting aspects of the complete design, while the other setup only considers the wireless aspects. It was important to be able to evaluate the two main parts of the design separately as they are not theoretically dependant on each other to function. The purpose of the energy harvesting block, and energy storage block, is to generate a stable output voltage. The purpose of the wireless block is to actually transmit data, given that a stable 3 V is available. These two can with advantage be analysed separately.

8.1 Part 1 - Energy Harvesting

8.1.1 Measurement setup

In order to evaluate the performance of the harvesting circuit we had to be able to see the voltage levels in real time to see how they behaved while the circuit was being used. In particular, the voltages $V_{IN}$ and $V_{CC}$, which corresponds to the input and output side of the energy harvesting blocks, were measured simultaneously. A 200 MHz digital oscilloscope with 2 GS/s was used to plot the two voltages. In the graphs below the yellow plot corresponds to $V_{IN}$ and the blue plot corresponds to $V_{CC}$. It is important to mention that even while we are not actively evaluating the wireless block of the design in test, it still had to be present and operating during these tests in order to provide a more realistic operating scenario.

There are essentially two different scenarios that we wish to look at:

- Cold Boot sequence
- Warm Boot sequence

A cold boot sequence represents the scenario where the whole circuit has to charge up and then boot without any energy being present in the storage capacitor. This is arguably the most common, and thus important, scenario since the capacitor will discharge relatively quickly after usage. Since it is not known at this time what the optimal capacitance value for the storage capacitor is, three different values were tested. In this case 4.7µF, 47µF and 470µF were used.

A warm boot sequence represents the scenario where the storage capacitor has not yet fully discharged from the last time the circuit was used. How often this scenario occurs
depends on the product that the technology ends up being used in, but there could be cases where you would want increased responsivenes for products that are used often within a short period of time. Of course, 4.7µF, 47µF and 470µF were used here as well in order to get a fair comparison. Keep in mind that the size of the storage capacitor is also the factor that actually determines how long the circuit can be in a ”warm boot ready” state. A 5 second waiting period was chosen as the definition of a warm boot in this experiment.

This means that in total six measurements had to be taken and plotted. In these plots, the x-axis corresponds to time in units of 10ms, while the y-axis corresponds to the voltage in units of 200 mV. In each of the six tests made the generator was rotated at a speed of 60 RPM for a duration of 0.5 seconds. This was chosen, with reference to previous reasoning, since it a quite comfortable and normal speed at which a human would manually turn a knob at.

The Wireless Block was configured to start advertising at an interval of 25ms as soon as it has completed its booting sequence. The booting sequence will start as soon as the Energy Harvesting Block activates the 3,3V on the V_{CC} line.

8.1.2 Measurement data

Fig 7. Cold boot sequence plot of V_{IN} (yellow) and V_{CC} (blue) using 4.7µF capacitor. The y-axis shows voltage at 2V per segment and the x-axis is time at 100 ms segments.
Fig 8. Cold boot sequence plot of $V_{IN}$ and $V_{CC}$ using 47uF capacitor. Axes same as Figure 7.

Fig 9. Cold boot sequence plot of $V_{IN}$ and $V_{CC}$ using 470uF capacitor. Axes same as Figure 7.
Fig 10. Warm boot sequence plot of $V_{IN}$ and $V_{CC}$ using 4.7uF capacitor. Axes same as Figure 7.

Fig 11. Warm boot sequence plot of $V_{IN}$ and $V_{CC}$ using 47uF capacitor. Axes same as Figure 7.
8.1.3 Data analysis

When selecting the 3.3V output voltage the LTC3588-1 has an Undervoltage Lockout Threshold ($V_{UVLO}$) typed at 5.05V for rising flank and 3.67V for falling flank. What this means is that the circuit will not begin the voltage conversion until this threshold has been passed on the input voltage. Similarly, in the opposite scenario, the circuit will cut off the conversion as soon as the voltage drops below 3.67V, although keep in mind that these are type values and not absolute values.

This threshold behavior is something that can be seen clearly in all six of the graphs gathered during the experiments. In Figure 7 we can see that as soon as the generator is rotated the $V_{IN}$ voltage immediately start to increase, but it is not until 60ms after that point that the voltage reaches 5V and the $V_{CC}$ 3.3V is activated. After a total of 460 ms, at the end of the rotation sequence, the voltage has dropped back down to 3.6V, at which point the conversion will stop, causing the $V_{CC}$ to shut off.

Arguably the most important part of the analysis is to look at how the capacitance value affects the time from the start of the rotation sequence until the chip in the Wire- less Block can actually start its booting sequence. The shorter you can make this time,
the better the experienced responsiveness of the product will be for the user. In table 2 you can see the times for the two different product booting scenarios for each capacitance value.

<table>
<thead>
<tr>
<th>Capacitance value</th>
<th>Cold Boot</th>
<th>Warm Boot</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7µF</td>
<td>60 ms</td>
<td>38 ms</td>
</tr>
<tr>
<td>47µF</td>
<td>64 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td>470µF</td>
<td>92 ms</td>
<td>32 ms</td>
</tr>
</tbody>
</table>

Table 2. - Comparison of time until boot from time of rotation start.

From the values in the table it is apparent that there is not that much difference in the start-up time for cold booting sequences when comparing 4.7µF and 47µF. The reason for this is that the generator in this case has the ability to provide enough continuous current in order to make up for the additional current needed to charge the larger capacitor. All the user would notice in this case is a very slight increase of rotational resistance when turning the knob. What may seem odd though is that, according to the table, the warm booting time is shorter when using 47µF rather than 4.7µF, which seems counterintuitive. This would of course not be the case under ideal scenarios, but in our case we are seeing this behavior simply because the concept of warm booting is not really applicable to this particular parameter setup when using such a small capacitor since the capacitor loses most of its charge within the 5 seconds. The 4.7µF capacitor cannot hold enough charge from a previous boot to really benefit on a succeeding boot. It also discharges so fast that it would be hard to find a scenario where a user could benefit from it. At that size, the capacitor functions more as a filter capacitor rather than anything else.

By looking at the figures we can clearly see that the storage capacitor is discharged very quickly when using the 4.7µF value. Comparing Figure 7 and Figure 8 for example shows two very different curves. In the first one, using 4.7µF, the voltage drops off roughly at the same speed as it built up with. This means that it closely follows the output voltage of the generator, thus demonstrating that the capacitor provide little to no benefit to the energy storage part. In the second one the voltage instead slowly decreases after reaching its peak indicating that as soon as the generator stops providing energy the capacitor instead can kick in and supply the system using the built up energy. So what this effectively means is that when using 47µF we can continuously operate the system and send data for a decent amount of time, 1.6 seconds in this case, after only a
quick 0.5 second turn of the knob.

Now, let’s turn our attention to the setup using the 470µF capacitor. In Figure 9 there are two observations that are particularly worth noting. The first is that now when using the much larger capacitor there is actually a noticeably longer delay on a cold boot. The registered time is 92 ms which corresponds to a 53 percent and 44 percent increase over the other two respectively. Remember that the aim was originally to keep the total latency of the whole system to at most 100 ms and if we are spending 92 ms of that solely on activating $V_{CC}$ then it only gives us 8 ms to perform the software boot, which is not feasible. The second observation is that even though the circuit is busy sending data at a rapid pace, the voltage is only declining at a very slow rate. For this particular case the system stayed powered on for roughly 17 seconds which is quite impressive for only a 0.5 second turn of the knob. So even though we only saw a 43 percent increase in start-up time, we managed to get roughly 960 percent increase in execution time.

It may sound strange, but when using the 470µ capacitor the system is generating more current than is actually needed. To keep the system powered on for 17 seconds could be great if you actually had any useful operations to perform during that time, but for our application that time would just be wasted since the user would not want anything to happen after the point when the rotation has stopped. For this type of product we value the shorter boot time more than we value the extra 960 percent of possible execution time, but we also acknowledge that this could prove useful for many other applications.

8.2 Part 2 - Wireless

8.2.1 Measurement setup

For the wireless part you mainly have to evaluate the current consumption. For this the current drawn directly from the $V_{CC}$ was measured, using a current to voltage converter, and plotted for a few common scenarios. Apart from the current consumption, it was also important to see how much time was needed in order to perform the given tasks, which can also be derived from the plots.
8.2.2 Measurement data

Fig 13. Booting sequence of the SoC.
8.2.3 Data analysis

Figure 13 shows a plot of the current consumption during a booting sequence of the wireless block. The peak at the start, near $t = 3819$, is a current peak caused by the 
Inrush current, also called switch-on surge, which is an instantaneous input current peak drawn by an electrical device when first turned on. In this case this is mostly caused by the DC-DC converter when it is activated, which unfortunately cannot be circumvented. After this peak you will see a 100 ms delay before the booting actually begins at $t = 3922$. The delay was actually added to the boot ROM code for the purpose of allowing time for the $V_{CC}$ line to fully stabilize before initiating the boot. However, it turns out that this is not needed in this case since the $V_{CC}$ line will already be stable once it is activated by the Energy harvesting block. So, we ended out opting away from this and thus this delay will be removed in a final design. So, for the purpose of making a fair evaluation of the data, we can assume that 100 ms can be subtracted from the booting sequence.

At $t = 3941$ the first data packet is sent and after that one additional packet is sent roughly every 25 ms as the knob is turned. Given that the power line is activated at $t = 3819$ we get a total of 122 ms from power on until the first packet is sent. According to previous reasoning we can subtract 100 ms from that. So in total we estimate that 22 ms is the total time needed for the Wireless block to boot and send the first data packet.

From the plot we can also see that during this sequence the total electrical charge consumed amount to 68 $\mu$C, of which 32 $\mu$C were used during the initial 100 ms delay. Since the delay is not included we can subtract that, which leaves us with 36 $\mu$C. If we convert that into joules, by multiplying it with the voltage (3V), we end up with 0.108 mJ. Remembering that we in section 5 talked about a previous study that achieved 0.78 mJ for a similar scenario this is clearly an improvement.

8.3 Discussion

By combining the results from part 1 and part 2 it is clear that the goal of keeping the total system latency under 100 ms is achievable. For the Energy harvesting block, using the 47$\mu$F capacitor, we have 64 ms latency. If we add to that the 22 ms needed by the Wireless block we end up at 86 ms which is well under the set limit.

The test results, and the analysis of them, clearly proves that this particular approach
of energy harvesting definitely has potential and could turn out to be useful in many fields of applications. As stated, it is definitely applicable to scenarios where a low system latency is desirable, proving that it is feasible for use specifically with the kind of products that was studied and proposed in this thesis. There should also not be any particular reason for why this approach could not be used in a wide range of other products and applications. In fact the results actually shows that for other applications where response time is not of a concern, you can achieve great power gains by accepting a bit higher latency.

9 Future Work

While the results do show that the technology, as constructed, is sufficient, there are however a few future improvements that would greatly benefit a product of this kind.

9.1 Knob position

With the current setup there are a few obvious drawbacks and among those is the fact that we cannot know how fast the knob is rotated, in which direction it is being rotated, nor at what position it is located at. The only information that we have is whether it is being turned or not, meaning that it would not matter how fast the end user rotate the knob - the results would be the same regardless. This is of course not ideal and all three of these drawbacks could be solved if we just had a way of knowing the position of the knob at all times. If you in every wireless packet also included the position then we would be able to derive the speed and rotation direction as well. To support a full 360 degree resolution we would have to add 9 additional bits to the protocol, something that arguably would bring great value.

There are many ways to decide the position, but two in particular comes to mind. The first one is to use a resistance track along the outer perimeter of the internal circuit board and then have a spring loaded contact surface that drags along against the resistance track as the knob is being turned. By doing this you should get a variable resistance that can be mapped against a degree value. To measure the resistance a so called Wheatstone bridge could be used for example.
Figure 13 shows an example setup where the unknown resistance $R_X$ can be calculated by measuring the voltage between the two points $P_1$ and $P_2$.

The second option would be to use a more advanced technique for deciding the position. In theory, using a 6-Axis Inertial Measurement Unit in combination with a 3-axis Geomagnetic Field Sensor should provide you with enough data in order to mathematically calculate the correct position. It is however unclear how reliable and accurate those results could be made.

9.2 Harvesting thresholds

One inherent problem with the proposed setup is the relatively high Undervoltage Lock-out Threshold values of the TC3588-1. The reason why this is so unfortunate is simply due to the fact that they are voltage thresholds rather than current thresholds. The point here is that the input voltage to a circuit does not necessarily have to reflect on how much current that can be drawn. In our case we know for sure that we would be able to supply enough current far below the 5.0V threshold, so in theory the start-up latency could be drastically decreased if we were just able to lower the threshold.

As it turns out this is in fact not an easy problem to solve. Ideally you would want to use a harvesting IC that has lower thresholds and while there are IC available that accomplish this, they also have much lower Maximum Operating Voltage. For example, another chip available from Linear Technologies, the LTC3105, can operate on voltages as low as 250 mV. The problem with using this particular chip is that it can only operate
safely on voltages up to 5 V. In fact anything above 6 V is bound to cause permanent damage to the circuit. It is clear that this would not work as our current setup can reach voltages of up to 20 V.

For an optimal solution one could look at maybe combining two different circuits, one that operates at the lower interval and one that operates at the higher interval, and then tie them together somehow to achieve a seamless integration that can function within the whole voltage interval. This is however bound to turn into a very difficult problem to solve and successfully combining two circuits would require much work. This is simply not within the scope of this Thesis.

9.3 Solid state batteries

As noticed when analyzing the results, depending on the chosen setup, we do have the ability to generate much more energy than the energy needed to transmit the data at the particular time of use. Admittedly, the purpose of this thesis was to construct a product without a long term energy storage, but the fact remains that if we have the ability to generate more energy than needed, then perhaps storing it for future use could be a good improvement to the usability of such a product. For example, you could incorporate a single push button that can function as an on/off switch that is charged by the dimmer itself. So as long as you use the dimmer often enough, you could also have enough energy to allow for a power switch as well.

In recent years the development of so called Solid State Thin Film batteries has made great progress. These rechargeable batteries are very compact, just a few square millimeters in size, and can be placed directly on a PCB with strict size limitations. Despite having a relatively small storage capacity, typically around 5-50 $\mu$Ah, they have the benefit of quick recharge times and a great number of lifetime recharge cycles. These batteries would definitely be worth investigating further for a product like this.
10 Conclusion

With the work done in this thesis project we have successfully implemented a fully functional proof of concept hardware and software combination that satisfies the requirements stated in the thesis objective. This lends us to believe that the concept of energy harvesting is definitely applicable to real world applications, such as wireless peripherals, by making use of just-in-time energy generation without long term interim storage. If someone wishes to implement a product based on this technology then careful consideration is needed on both the hardware and software aspects since each different application has its own challenges and requirements. However, it should be achievable as long as the proposed solution is properly fine tuned and adjusted.

Parameters such as rotation torque, rotation speed and overall product size are key to deciding the power output that is achievable for any given product. Other parameters, such as system latency, can be altered in order to adjust execution time. Perhaps the most interesting aspects of this is that it allows for making battery-less products without any negative impact on the user experience, which could possibly add to the "wow-factor" of any given product. In more serious perspective this could also help to reduce the toxic battery waste and significantly extend product shelf life.
11 Reference list


