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Industrial Electrical Engineering and Automation

Energy Harvesting in Wireless Applications

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Table of Contents

Abstract

The objective of this thesis has been to study how extensive current research has gone within energy harvesting and to investigate a solution for making the OLP425 (a sensor module developed by ConnectBlue AB) independent of a conventional battery as energy source, whilst staying wireless. This has been done by investigating the amounts of energy that is available from our surroundings (e.g. solar radiation, thermal gradients, and radio waves) and how suitable the methods are for supplying the OLP425. A solution based on a photovoltaic cell was chosen and an electrical circuit was designed around it, powering the OLP425 and recharging a Li-ion rechargeable battery. It was successful in powering the OLP425 but limited by the sensor module's duty cycle. Whilst being a successful solution there is still more to investigate in the field that includes other energy harvesting methods where some require a larger business model to implement.

Preface

This thesis has been done at ConnectBlue AB in Malmö with guidance and assistance from my supervisors Gunnar Lindstedt at the division for Industrial Electrical Engineering and Automation at LTH and Mats Andersson at ConnectBlue. I would like to thank both IEA at LTH and ConnectBlue for presenting this opportunity for me to do a master thesis within energy harvesting.

Introduction

One of the first energy harvesting devices was the dynamo, invented 1831 by Michael Faraday, which converts kinetic energy into a current. Energy harvesting principles can however even be dated back to the invention of the windmill and waterwheel. Since then, energy harvesting has been an area of interest for research but it has had its limitations. In comparison to the power consumption of electronic devices, such as a laptop or cellphone, the amount of energy available in our surroundings is not enough to power the devices. With environmentally friendly aspects being an increasingly critical topic, renewable energy and energy conservation has gained a lot more focus and resources for research. Recently, the development of microelectronics has led to the power consumption being so low, that renewable energy from sources as wind, water, geothermal and solar energy are now viable options as primary energy sources instead of e.g. batteries.

Since there is energy in our surroundings in so many different forms, the main challenge will be to differentiate them and analyze what form that would be most beneficial for the OLP425. Different forms of energy sources introduce their own set of limitations while they all have a varying range of distinctive advantages. With recent progress within the field of energy harvesting, supplying the system with current is not the challenge but rather at which rate that the current can be supplied. Having a widely spread wireless sensor networks with several nodes harvesting energy from the surroundings also implements complexity in the way of that every node face different situations for gathering energy from their surroundings which also varies with time in a sometimes nondeterministic matter.

Background

Assignment

It was proposed to make the OLP425, a product developed by ConnectBlue, independent of a conventional non-rechargeable battery and to investigate whether it could be supplied by ambient energy in its surrounding by implementing energy harvesting. The thesis wasn't defined further than this.

My personal interpretation of this task is to find an energy source for energy harvesting that can sustain the requested OLP425 and at the same time have viable environmental conditions. Different energy sources will be compared in how much power that can be achieved from them and to what extent the presence of the energy sources can be encountered.

Purpose

One of the main reasons that drives the development within the field of energy harvesting is to make wireless sensor networks independent of conventional batteries and therefore requiring less maintenance. The work of replacing batteries is both costly and time consuming, especially since many wireless sensor networks can contain sensor nodes in the magnitude of thousands. Being able to supply the sensor nodes through energy harvesting can prolong the lifetime of a sensor node's battery and thus also decrease the replacement rate of the sensor and thereby also being a more environmentally solution.

OLP425

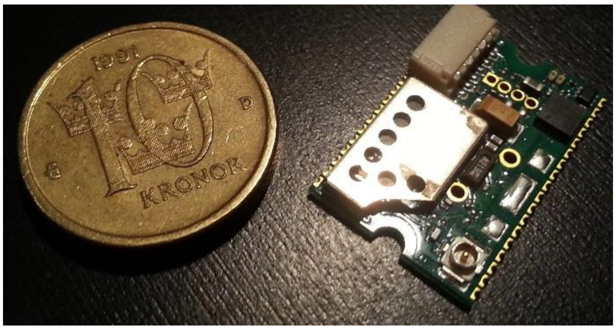


Figure 1: Picture of the OLP425

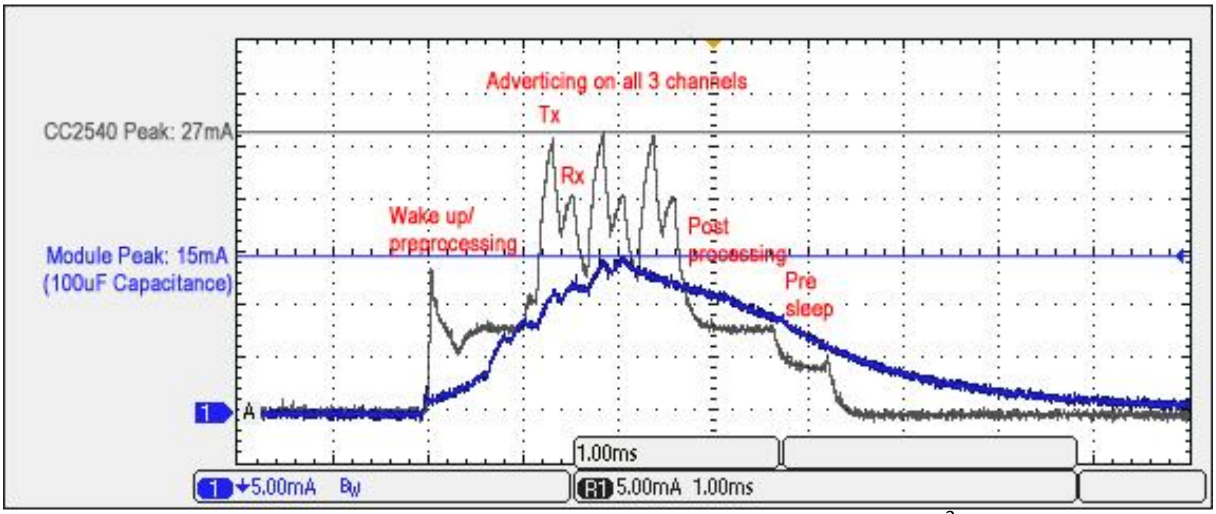
The OLP425, cB-OLP425, is a low energy, single-mode platform module that is expandable with several accessories. The OLP425 can be mounted with a battery holder, temperature sensor, accelerometers and other sensors to tailor the needs of the client who purchases it. The low energy consumption is achieved by the low energy Bluetooth protocol. This protocol is focused on a very rapid and short radio activity and sleep times with low energy consumption in between. During the communicative and data processing phase, the unit is consuming almost the same amount of energy as a classic Bluetooth application and likely even uses more power in comparison, due to its protocol being optimized for small bursts of energy[1].

The parameters of operating the OLP425 is as following:

Table 1: Input/output signals. Vin = 3.0V[2].

Symbol	Parameter		Value	Unit
V_{IN} Low	Logic LOW level input voltage	Min	-0.3	V
		Max	0.5	V
V_{IN} High	Logic HIGH level input voltage	Min	2.5	V
		Max	3.3	V
V_{OUT} Low	Logic LOW level output voltage	Max	0.5	V
V_{OUT} High	Logic HIGH level output voltage	Min	2.4	V
I_{IO_20mA}	Sink and source current pin J6-2 and J6-9	Max	20	mA
	Voltage drop @ I_{IO_20mA}= 20mA	Typ	0.3	V
I_{IO_4mA}	Sink and source current all other IO pins	Max	4	mA
	Voltage drop @ I_{IO_4mA}= 4mA	Typ	0.5	V
$R_{IN\_PULL-UP}$	Input signals (including $\overline{RESET}$) internal pull-up	Typ	20	kohm
t_{Reset}	Reset pulse length	Min	1	us
V_{ADC}	ADC Analog input pins	Min	0	V
		Max	Vin	V
	ADC number of bits	Min	7	bits
		Max	12	bits

The OLP425 can be powered with a 3.0 V battery. During high current periods, an internal capacitor in the OLP425 will act as primary power source while during low current periods



the battery will be the primary power source and recharge the capacitor[3].

Figure 2: cB-OLS425 current consumption during advertising. There are no documented current consumption for the cB-OLP425 but it can be compared to the cB-OLS425 since they have the same current consumption, if cB-OLP425 is loaded with the same firmware as the cB-OLS425. The grey curve is moment radio consumption and the blue is smoothed-out because of the 100uF capacitance to offload the battery. A 10ohm resistance is used as internal power source resistance in the measurements. The energy consumption (mAh) is the integration (area under the curves) of the curves.

The OLP425 is sold as-is and it’s up to the customer to implement it and decide how the duty cycle of its active phase should be scheduled. With a general and conventional coin cell battery, the lifetime of it can vary from 1-10 years before having to be replaced but this can be both greater and lower depending on the duty cycle. Values of as low as 1µA has been measured as average current while in sleep mode. With the OLP425 being active for approximately around 0.5 ms (as read from **Figure 2**), with a duty cycle of once in a minute, it will be in its SLEEP phase for approximately:

$$100 * \left(1 - \frac{0.5 * 10^{-3}}{60}\right) = 99.999\%$$

Thereby, the power consumption while in the SLEEP phase sets the limit of power consumption.

Energy Harvesting

Energy Managing Theory

With energy existing in so many different forms and at so very different circumstances, managing how to store it can be approached in several ways. Conventional batteries offer among the higher energy densities available for storage for portable devices and can also come in varieties that are rechargeable. However, energy density might not be the limiting factor.

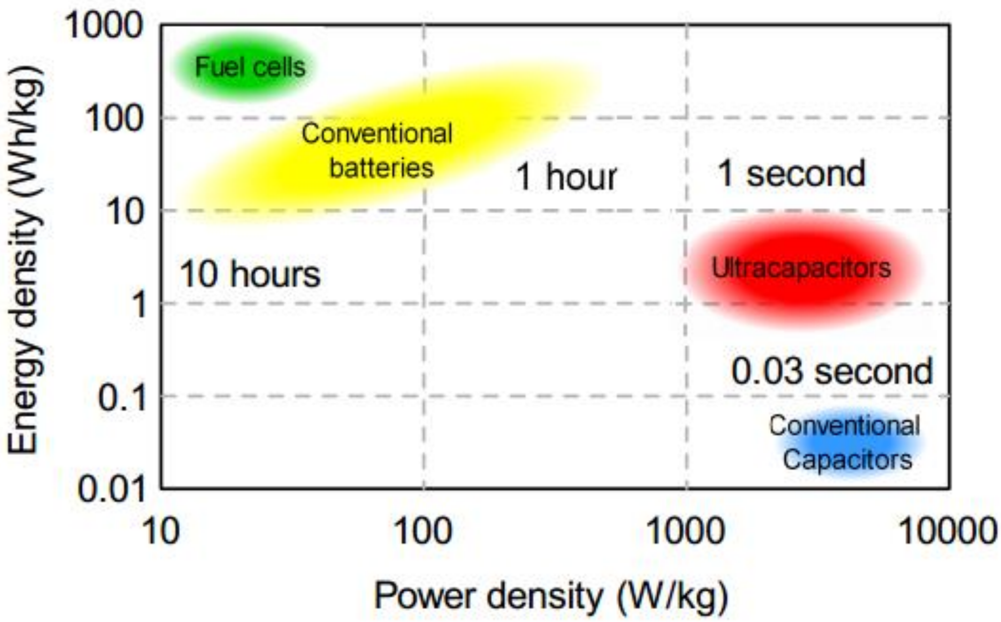


Figure 3: A ragone chart for high power applications[4].

Due to most of the energy harvesting is meant for low energy wireless sensor nodes which are supposed to be deployed and forgotten to manage themselves, other problems may arrise. Factors such as leakage current, lifetime, power density and recharge cycles become increasingly important. Batteries and capacitors distinguish themselves by more or less acting as each other's counterparts when it comes to how they can store energy, as seen in **Figure 3**.

Different batteries can e.g. have a self-discharge rate that can vary from 30%[5] (for some Ni-MH batteries) to 2-3% (for some lithium batteries) per month. A battery has a limited lifetime which is measured in how many recharge cycles it can go through. As an example, if a battery such as a Ni-MH battery has a lifetime measured in 500 recharge cycles and a solar cell is used for recharging; if a charge cycles is completed and consumed in a day, the lifetime of the battery is limited to 500 days. A supercapacitor on the other hand can withstand virtually unlimited amounts of charge cycles and doesn't need extra implementation of tickle charging (to avoid damage from overcharging), since it is not subject to overcharge as a battery. A supercapacitor does however also come with its limitation as low energy density compared to battery, a linear discharge voltage and a relative high self-discharge. [6] Since most of the research of energy harvesting is focused towards implementing self-sustaining wireless sensor nodes and that low-energy wireless sensor nodes often function by sleeping about 99% of the time, a combination of battery and supercapacitor is often implemented. The battery handles the steady state sleep mode of the sensor when it only requires a low current whilst the supercapacitor provides with smaller bursts for when the sensor "wakes up" to broadcast.

Besides using batteries or capacitors to store the energy it is also important how the energy is handled with our without these. At times, an energy storage wouldn't even be needed and three different ways of managing the energy with or without a storage will be discussed[7]:

1. Harvesting system with no energy storage:

This case considers a system that has a transducer to harvest the ambient energy from its surroundings and the energy is directly used by the load without any intermittent energy storage. One example that has been using this method is for example a water-powered flour mill, that doesn't operate unless water (energy) is added to the system.

2. Harvesting system with energy storage and $P_{needed} > P_{harvested}$:

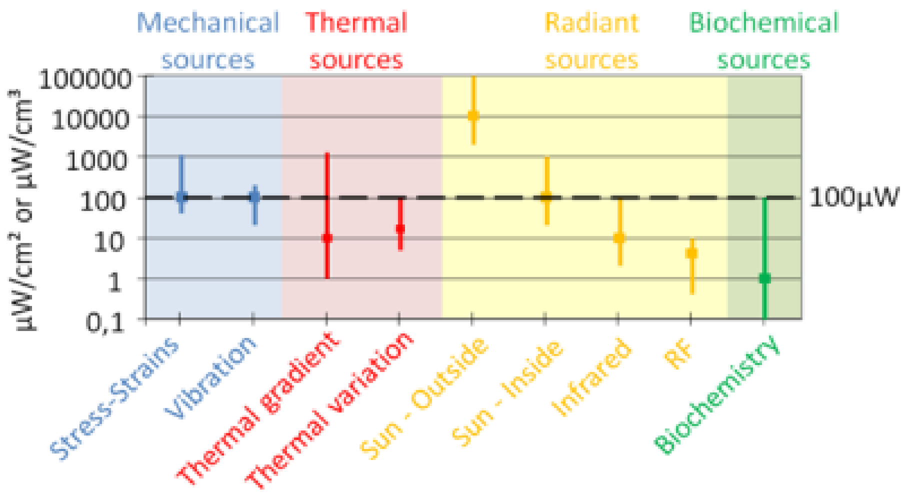
It is theoretically possible to power any type of system, as long as its power is controlled in a way so that the system cannot take action until the energy buffer is on the required level of operation, to go back into sleep mode again awaiting the next time the energy buffer is at the same level. This implementation puts limitations on how the system can operate and can in many cases be too restrictive. However, with this implementation the system gets a lot more robust against disturbances in the harvested energy by just waiting a longer time until next possible time of operation and the harvesting method can be implemented in a lot more different areas where it earlier weren't high enough of ambient power density.

3. Harvesting system with energy storage and $P_{needed} \leq P_{harvested}$:

The more ideal situation when it comes to managing energy is that the harvested amount of energy is either equal to or exceeds the needed energy. Due to the characteristics of capacitors and batteries with leakage and fluctuations in the amount of energy harvested, this is in reality not always possible to achieve.

In this report, situation no.3 will be strived to attain, since it gives the OLP425 more flexibility of how its duty cycles can be scheduled. The first options is also viable but since it will put higher demands on the ambient energy, it will also put more restraints in environments that the OLP425 can be implemented in. Option no.2 is viable in a way that it could make the OLP425 implementable in virtually any situation with almost any method of energy harvesting. However, the OLP425 is proposed to be the factor that should decide when it operates, in this case, and thereby this situation falls short.

Energy harvesting became a much more interesting field of research and there are already experimental results obtainable to get a good first look into how the different



energy conversions might perform.

Figure 4: Power density from ambient sources before conversion[8]

According to (Sebastien Boisseau, http://www.embedded.com/, 2012)[9] the amount of energy achievable from different sources roughly averages to about 10-100 μW per cm^2 or cm^3 of the energy harvesting module, as shown in **Figure 4**, when designing for wireless sensor node networks. The results varies with the constellation and circumstances. With regards to 10-100 μW being far less than what many applications need it can still theoretically be used to virtually power any source by charging a battery to the minimum requirement of power needed and thereafter only using it “when available”. This is limiting for the frequency of the duty cycle but shows the possibilities of energy harvesting, especially where sensor node networks implementing low-cost Zigbee[10] apply a standard where the sensor nodes are active in a sleeping state the majority of their time.

Available Sources

Virtually everything in our surroundings are different forms of ambient energy. When it comes to energy harvesting, the forms of energy considered as “reservoirs” will be emphasized and by that the four categories photonic, kinetic, thermal and electromagnetic sources are included. With photonic sources both the sun and artificial light are included. Wind, flowing water and vibrational or oscillatory motion generated are accounted for as Kinetic energy. Thermal energy is any potential temperature gradient and electromagnetical sources are magnetic fields generated from machinery or wires. There are more sources of ambient energy that are potential subjects for being harvested but some ,due to this thesis being about exploring the implementation of the OLP425 from ConnectBlue which is most likely to be implemented indoors and potentially in an industrial environment, some of the sources are less likely to be found than others. Some sources also results in the energy harvesting becoming parasitic of another process whereas the intention of energy harvesting is supposed to use the abundant amounts of energy that otherwise goes to waste, without interfering with another vital process.

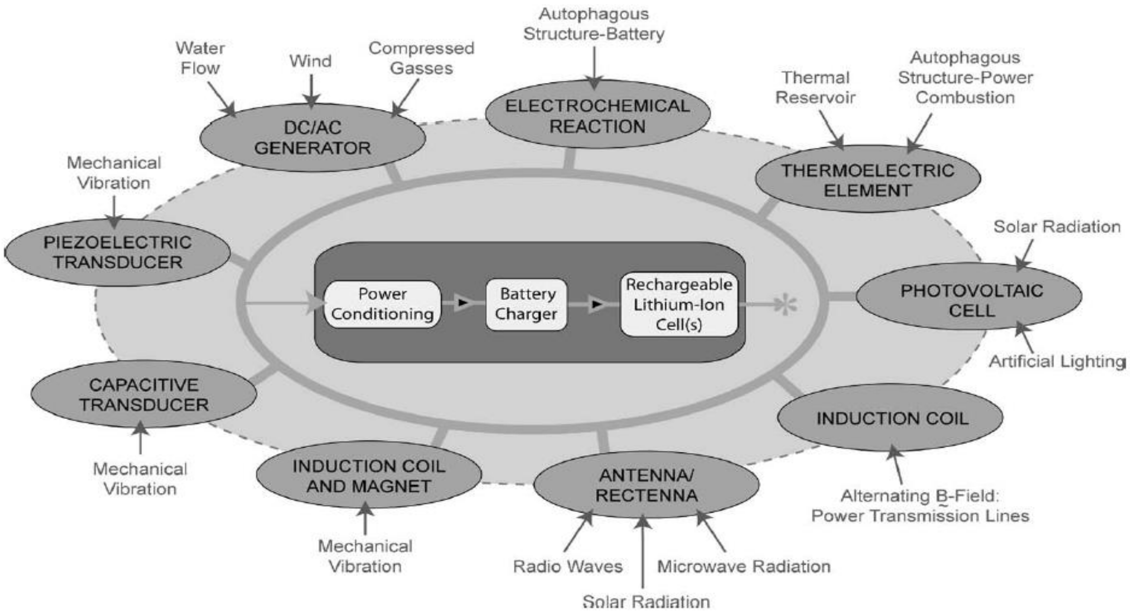


Figure 5: Various potential energy sources for energy harvesting[11]

Figure 5 gives a comprehensive overview of all potential source of ambient energy for energy harvesting. Many of the circumstances needed for some of the energy reservoirs are limiting in the way that they are not so often encountered in the vicinity of where an OLP425 would be implemented or that the energy harvesting easily becomes parasitic as in for example exploiting a chemical potency difference which easily influences the chemical process. Some of the different energy sources can also be harvested with the same means of transducers, as in for example naturally magnetic fields being harvested from a coil or by implementing a coil with a magnet passing through in a vibrational or oscillating movement.

Solar

The practice of converting light into electricity is at present an experienced and well known discipline. Photovoltaic cells consist of materials that exhibit the photoelectric effect, which causes them to absorb photons from the light and release electrons. These electrons can later be put to use as electricity. This is being realized by the photoelectric material consisting of a thin semi conductive layer, positive on one side and negative on the other side. When connected to a circuit, the layer of photoelectric material will generate a current from the light by causing electrons getting knocked loose from the atoms in the material.

Photovoltaic cells can easily be connected and mounted together, to build a larger array of cells. In general, the larger area of the array, the more electricity can be produced.[12] The power that can be harvested often ranges at about 100 mW/cm^2 directed direct at the sun a bright day and 100µW/cm^2 in an illuminated office[13]. Many photovoltaic cells are used in conjunction with Maximum Power Point Tracking (MPPT), which is an algorithm for extracting the maximum amount of available power that a photovoltaic cell can produce at the given circumstances.

Maximum Power Point Tracking

The maximum power achievable from a photovoltaic cell varies with solar radiation, ambient temperature and solar cell temperature and is therefore seldom attained by the photovoltaic cell itself without the implementation of a MPPT (Maximum Power Point Tracking) algorithm. For every combination of these complex conditions, a photovoltaic cell always has a single operating point where the current [I] and the voltage [V] result in a maximum power output. The load resistance corresponds to this according to Ohm´s Law $U = R * I$ and where the power is given by $P = U * I$. A photovoltaic cell has approximately an inverse exponential relationship between the current and voltage at the MPPT region of the curve. The power delivered is optimized where the derivative $\frac{dI}{dV}$ is equal and opposite the I/V ratio, as shown by **Fig 6**.

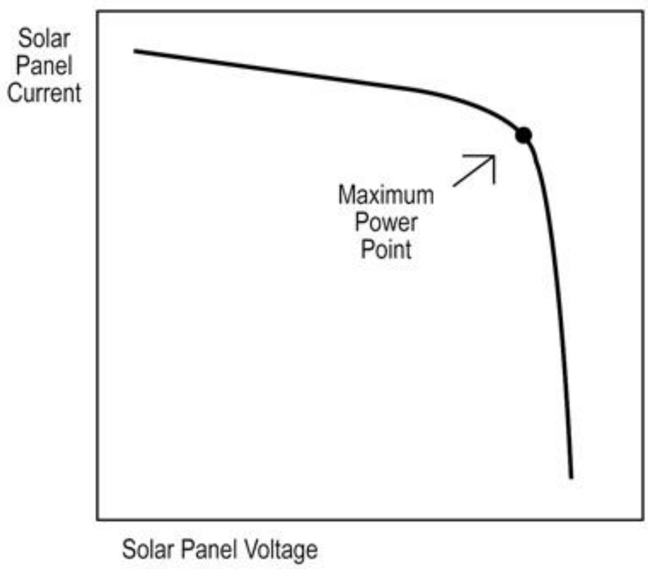


Figure 6: Schematic graph of the maximum power peak[14].

There are plenty of different MPPT algorithms and many controllers implement more than one algorithm at the time, switching between them based on the operating conditions of the photovoltaic array. Two of the most used algorithms are Perturb and Observe and Fractional Open-Circuit Voltage. Since the maximum power point voltage V_{MPP} has a linear correlation to the open circuit voltage V_{OC}, the Fractional Open-Circuit Voltage algorithm comes down to:

$$V_{MPP} = k_V * V_{OC}$$

Where the constant k_V depends on the type and configuration for the photovoltaic array. The maximum power point is approximated by temporarily disconnecting the load to measure V_{OC} and calculate the operating voltage. This method presents a clear disadvantage by the power lost while disconnecting the load.

The Perturb and Observe method implements MPPT by incrementally adjusting the voltage from the photovoltaic array and then measures the power. The controller will keep to incrementally increase or decrease the voltage if it measures that the power as a result increases, until the power doesn't rise any further. This algorithm is the most common used MPPT method due to its ease of implementation. Perturb and Observe can result in top-level efficiency but comes with the drawback that the implementation can result in oscillations of the power output.

Kinetic

A physical movement, whether it be a vibration or a longitudinal motion, is an often overlooked process which can contain a lot of energy. There are several ways to approach the gathering of the process' energy e.g. having a piezoelectric crystal convert mechanical strain into an electric current or creating induction by having a magnet passing by or through a coil. Piezoelectric crystals are conventionally used as sensors for measuring physical strain. However, they have found new uses in the way that if they are placed in a process that puts constant and varying strain the signal may be used as a current source instead of the signal being used for reading[15]. Piezoelectronics have become increasingly popular due to being applicable in so many forms. Wearable electronics is one of the bigger fields for researching and 2001 a project was carried out where a pair of shoes were equipped with an integrated circuit, which used piezoelectric crystals to harvest energy from the shoes when they were used for walking[16] as shown in **Figure 7**. With this implementation of piezocrystals it was possible to harvest about 1.3 mW with a walking pace of 0.9 Hz whilst having a piezoelectric lead zirconate titanate under the heel.

Figure 7: Piezoelectric-powered shoes with its electronics mounted[17]

Supplying power by induction is also another widely used method in modern technology and it is now gaining grounds in microelectronics. In 1986 the wristwatch company Seiko, released its first wristwatch that was power by induction[18]. This was done by having magnets within the wristwatch that passed a coil whenever the wristwatch was in movement, thus charging the battery.

Radiation

Ambient Radiation

The major advantage of ambient radiation such as radiation from radio waves, mobile phone towers, television stations or Wi-Fi transmitters is that it can be found in many different environments, especially in the proximity to urban environment. Absorbing the radiation and converting it into electrical energy won't leech on any other process since most of the radio waves get absorbed by any object it is sent into, without the energy being put to use. The average amount of energy that exists in the radiation is relative low and often requires a large antenna to gather sufficient radiation for powering an electrical process.

Transmitted Radiation

Radio waves can however also be used as a mean for transporting energy if the transmitter sends the waves at a higher frequency than conventional radio waves transmitted from a radio tower[19]. In (Steven Percy, 2012) a transmitter was constructed to supply a sensor network with power. The transmitter was able to supply the system with sufficient energy, although it proved challenging since with higher frequencies on the radio waves, it had to pinpoint the location of the sensor, thus needing to prioritize which sensor to supply. This report focused in having a large source of power that distributes its energy to sensor nodes in its vicinity and even though the report shows that it is possible to sustain a sensor network, it is limited by the dissipation of radio waves over distance and the inefficiency of converting energy to radio waves to later convert it back to energy. To harvest energy from RF has yet a lot of research to be done but for the application of supplying a sensor network of OLP425 it is still a solution waiting to be done more efficient.

Whilst RF energy scavenging might seem problematic, a lot of ground is being gained within the field. With one of the most crucial parts of RF harvesting being the antenna, a proposed design[20] includes the use of coplanar waveguide[21] design as shown in **Figure 8**.

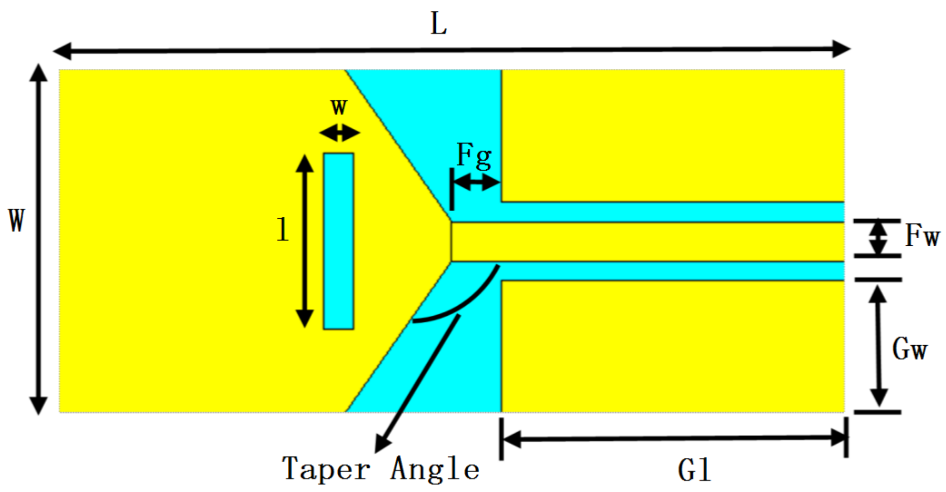


Figure 8: Antenna designed for coplanar waveguides[18].

The purpose was to achieve an antenna that could scavenge energy over a bigger bandwidth than many current antennas do in the small physical scale that they are built in for energy harvesting. With a PCB-size of L=8cm and W=3.5cm, this antenna was able to register frequencies from 1 GHz to 5.3 GHz, giving it a bandwidth of approximately 4.3 GHz. The rectangle slot was etched on the antenna to improve the performance of the antenna by increasing pass length of current flow and thereby increasing the current density. By using CST Microwave Studio, simulations were done for achieving the maximum power that the antenna could receive at 1 meter from the source which transmitted the radio waves. The achieved power found to vary between -12.39dBW/m^2 and -5.88 dBW/m^2 (17.61 dBm/m^2 and 24.12 dBm/m^2) which is approximately 255 mW as maximum power achieved. These

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}$$

values are at 1 meter distance from an emitting source and the amount of energy in the propagating waves drops off according to Friis Transmission Formula[22]:

Where, P_R is the power received by the antenna, P_T is the total power delivered to the antenna, G_T is antenna gain of the transmit antenna, G_R is the antenna gain of the receive antenna, λ is the wave length in the transmission medium and R is the distance between the transmitting and the receiving antenna. Friis Transmission Formula presupposes that there is free space and no obstacle in the path between the receiving and transmitting antenna and shows that the power delivered to the receiving antenna diminishes with the square of the distance. Roughly 80 µW was the maximum amount of power that was achieved at a distance from 50 meters. To be noted is that at longer distances, lower frequencies supplies the most amount of power in relation to higher frequencies. Even though sounding promising, this test was not done with ambient radiation but rather with having a power source supplying the power to the energy harvesting device.

Comparing the Different Sources

Before going too much into how the different sources will be compared, it will be discussed how there are different types of controllability and predictability when it comes to the energy feed. Whether or not the energy source is predictable or controllable can have major impacts on the energy harvesting even if the harvesting method itself is efficient in energy conversion. The energy sources will be classified and discussed as following[23]:

1. Fully controllable: Energy can be generated when desired and during predictable situations. An example would be a flashlight powered by Piezoelectronics where energy can be generated by the user, for example, simply shaking the flashlight.
2. Partially controllable: A constructed system that generates opportunities for energy harvesting. A radio frequency energy source that for example could be generated by a company's own wireless network. This creates opportunities for RF energy harvesting and even though the network's signal strength and expendability can be controlled, increasing its strength solemnly to harvest energy will result in a net loss of energy.
3. Uncontrolled but predictable: Solar energy is a good example of an energy source that cannot directly be controlled but we know the sun will come back after it's gone away for the night. There is an error margin since the sun does not always go up at the same time but since it's still predictable when looked at from a bigger perspective, it's still reliable.
4. Uncontrollable and unpredictable: An energy source that cannot be controlled to generate energy when desired and gives energy at times that cannot easily be predicted or that the model for predicting the energy is either too complex for implementation. Vibrations can during some circumstances fall under this category since the vibration pattern and therefore the energy received is at many times hard to predict and in some cases also not controllable.

Though controllability is desired, it is not nearly as important as predictability. Controllable sources often do not offer control in a way that benefits the system in a greater way, since controlling a system to generate more energy as a residuary product, will cause an energy loss compared to using that energy to the primary source. Predictability however becomes more important since the OLP425 does not have a standard environment of where it is implemented and thereby knowing what types of energy sources appear and knowing how they behave, becomes an increasingly important criteria.

Whilst many of the different available and potential power sources for energy harvesting poses different opportunities and drawbacks, this report will focus on the source that will the most suitable for supplying the OLP425 during deployment in a wireless sensor network. **Fig 7** is a reference from a study where a wireless ZigBee sensor which has an ACTIVE communicating state that lasts for 864 ms. The sensor consumes 54 µW in SLEEP mode and 23 mW during its ACTIVE state. The size of the energy harvesting devices in this analysis are 1 cm^2 for the solar and thermal scavenger and 1 cm^3 for the vibration harvester. Even though this sensor differs a lot from the OLP425, this graph still serves it purpose in giving an overview comparison on the different energy harvesting methods. Theoretically, as long as the method of harvesting energy can withstand the SLEEP mode's power consumption, the different methods of energy harvesting have a maximum duty cycle to which they can autonomously supply the system with energy. In such a case some kind of energy storage would still be required to supply the power during the ACTIVE state. With the case of an energy harvester autonomously supplying the system with energy, a capacitor, which has a cycle-lifetime much greater than that of a battery, would be ideal for managing the peak power consumption due to the capacitor not needed to be charged during the entire SLEEP state, thus reducing possible leakage current. The ideal situation would be to dimension the supercapacitor so that it at full charge, precisely corresponds to the power needed during the sensor module's ACTIVE state. In this way the supercapacitor will only be charged right as it's supposed to be used, to further reduce possible leakage current.

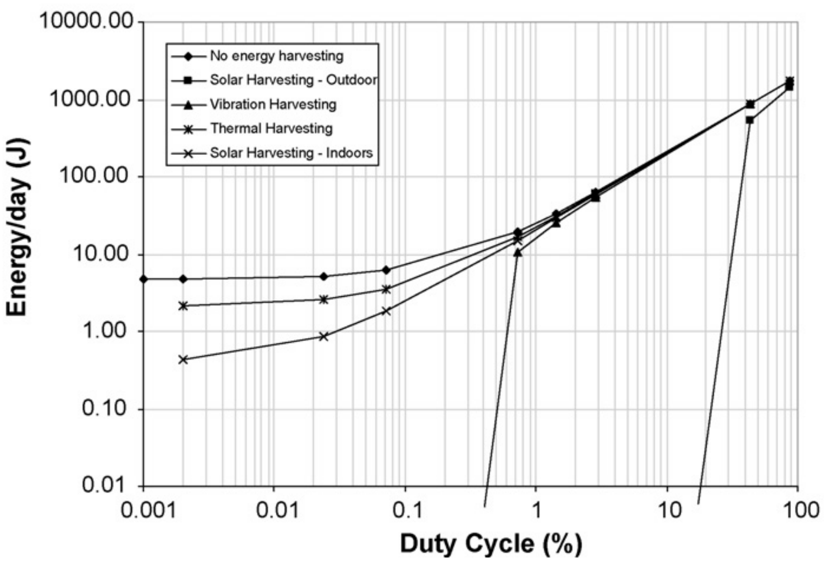


Figure 9: Daily energy consumed from storage vs on duty cycle (%)

Figure 9 gives a schematic view of the relevant energy harvesting methods, except radiofrequency harvesting, and the conclusion that solar harvesting or vibration harvesting seems to be the most promising alternatives.

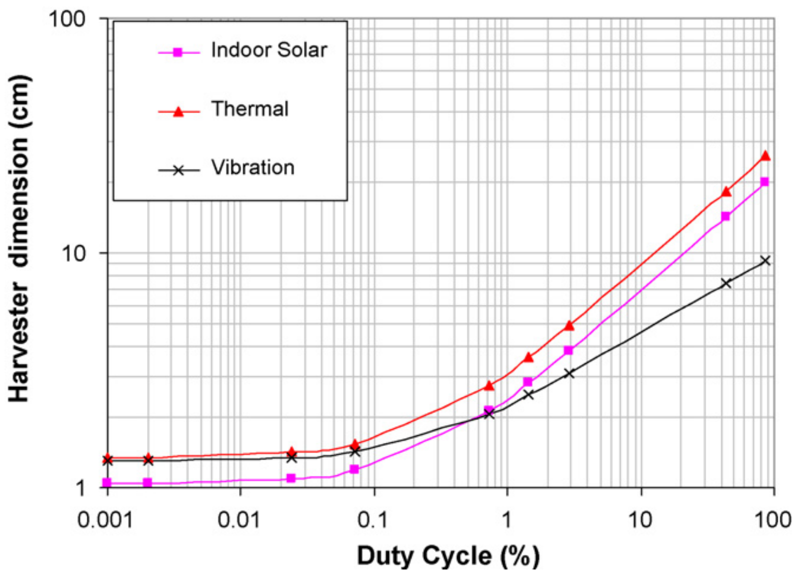


Figure 10: How high duty cycle an energy harvester can maintain, depending on the harvester's relative dimensions measured in cm.

As for harvesting ambient radiofrequency, the power density variation in different European urban environments is found to be between -60 dBm/m^2 and -14.5 dBm/m^2 which corresponds to 1 nW/m^2 and 35.5 µW/m^2. The maximum of power density is measured at 1.8-1.9 GHz, which is where the GSM1800 subsides (One of the two bandwidth-distribution fields for the European mobile communication system). Different approaches[24] [25] [26] all present that harvesting energy from ambient radio frequencies can, under ideal conditions, generate approximate 1 µW/cm^{2}.

For comparing the different methods of energy harvesting that are relevant for implementation together with OLP425, concept scoring will be used where the categories will be used as followed:

Maturity

How far the research has gone in the field and whether or not it seems to have stagnated. This is not an important criteria as the others since the main focus is to determine what, if any, method suits best for energy harvesting at present but still presents some interesting opportunities for what might come. The more mature the field is the more we know what we can expect as a result. Depending on the perspective it can be positive to either deal with a mature field or one that is still in an experimental stage. In this report, a mature field will be favorable due to it will be easier to predict the possible results.

Cost

How much the sensors and supplemental equipment cost to implement the solution. The cheaper the better. The sensors will be sold at bulks to companies which can vary from a selected few to thousands and thereby cost is of course of importance. The integrated circuits that regulate the harvested energy costs about the same and to present a figure, Linear Technology offers IC for these purposes that all cost about 5-8 USD. What separates the methods apart are the other main components needed. For the size that's suitable for energy harvesting in wireless sensor networks; a photovoltaic cell costs about 7 USD, thermoelectric modules approximately 30 USD, piezoelectronic energy converters about 65 USD and a RF harvesting circuit alongside an antenna can cost from 80 USD[27].

Power

The potential amount of power that is available for the harvesting method is one of the most determining factors since the sensor has to be able to be fed enough power to operate. The amount required varies depending on implementation and the more power that is available, the more configurations in the software can be run. Interpreting **Fig 3** gives a schematic overview of the different power levels available[28][29].

Ambient Conditions

How much the harvesting method suffers from disturbances in conditions and how often these occur. Since there is no general circumstances of environmental conditions, adaptability becomes the most determining factor. It is the customer who purchases the OLP425 that chooses what conditions to implement it and therefore it is preferred that it can handle as many different scenarios of environmental conditions as possible and how these conditions gets affected from outer disturbances. Ambient radio frequency is uncommon not to find, even though it can be drastically reduced by just encapsulating e.g the sensor module. Solar power can be harvested not only from direct sunlight but also from indoor lighting and therefore also exists to quite some extent. When it comes to an office environment (which is the most likely scenario for the OLP425 to be installed into) vibrations does perhaps not exists in a bigger extent and thermal gradients are mainly in the walls.

	Weighting	*Vibrations*	*Solar*	*Thermal*	*RF*
Maturity	1	3	3	2	2
Cost	2	1	4	2	2
Power	3	3	2	2	1
Ambient Conditions	4	2	3	2	3
Results		22	29	20	21

Table 2: Concept scoring between the different potential energy sources

The concept scoring shows that solar power has the most promising characteristics for this implementation. Vibration harvesting is indeed a strong candidate but it falls short in how it is restricted to being implemented on surfaces that vibrate and even though it performs really well during optimal conditions. Ambient radio frequency harvesting doesn’t supply enough power and today that is its major restriction, even though it is viable in the way of radio waves existing virtually everywhere in our surroundings. RF harvesting might be a lot more promising in the future due to power consumption of microelectronics might subside to the same level of where a RF harvester could provide the sensors’ power. RF harvesting can also combined with having a solar panel covered roof with several m^2 of photovoltaic cells and thereafter having an emitter to fuel each individual sensor node with the required power. This solution has a lot of power loss due to conversion efficiency but due to the sensors requiring a lot less power than what some m^2 of photovoltaic cells can harvest, the available power can almost be seen as infinite in comparison to needed power. This solution won’t be taken in consideration since it requires more of a full scale solution which is a lot more extensive not only in construction but as a business model.

The solution selected will include a solar panel, with minimum amounts of electronics required to introduce DC/DC boost converting and MPPT. A larger circuit which will include protection for the battery from over- or discharging will also be presented.

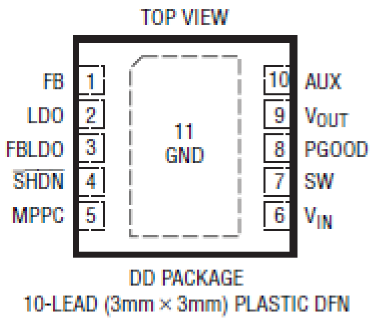
Method

The proposed solution for solar energy harvesting requires some type of maximum power peak tracking, a DC/DC converter and preferably a shunt charger, to protect the battery from potential overcharging. This circuit won't include a supercapacitor due to the main focus being on examining the potential available energy first. A supercapacitor will afterwards be implemented together with a battery, if there is enough time, to decrease power-losses when feeding the OLP425.

Linear Technology is a company who, amongst other IC, offers energy harvesting IC where the LTC3105 in this case will be used for MPPT and DC/DC converter and the LTC4070 will be used for protecting the battery from overcharging. All components were ordered through Digikey.com since they were the only retailers who had them in stock.

LTC3105

The lTC3105 is a DC/DC converter, with a varying efficiency around 90%, which can operate at input voltages ranging from 225 mV to 5V. It provides maximum power peak tracking (MPPT) with a low start-up voltage at 250 mV which enables operation directly from low voltage and high impedance power sources such as photovoltaic cells or thermoelectric generators. The MPPT is user programmable but will during this investigation be used with default settings. There is also a 6 mA auxiliary LDO that can be used for external



microcontrollers or sensors while main output is charging.

Figure 12: Top view of the LTC3105's pins.

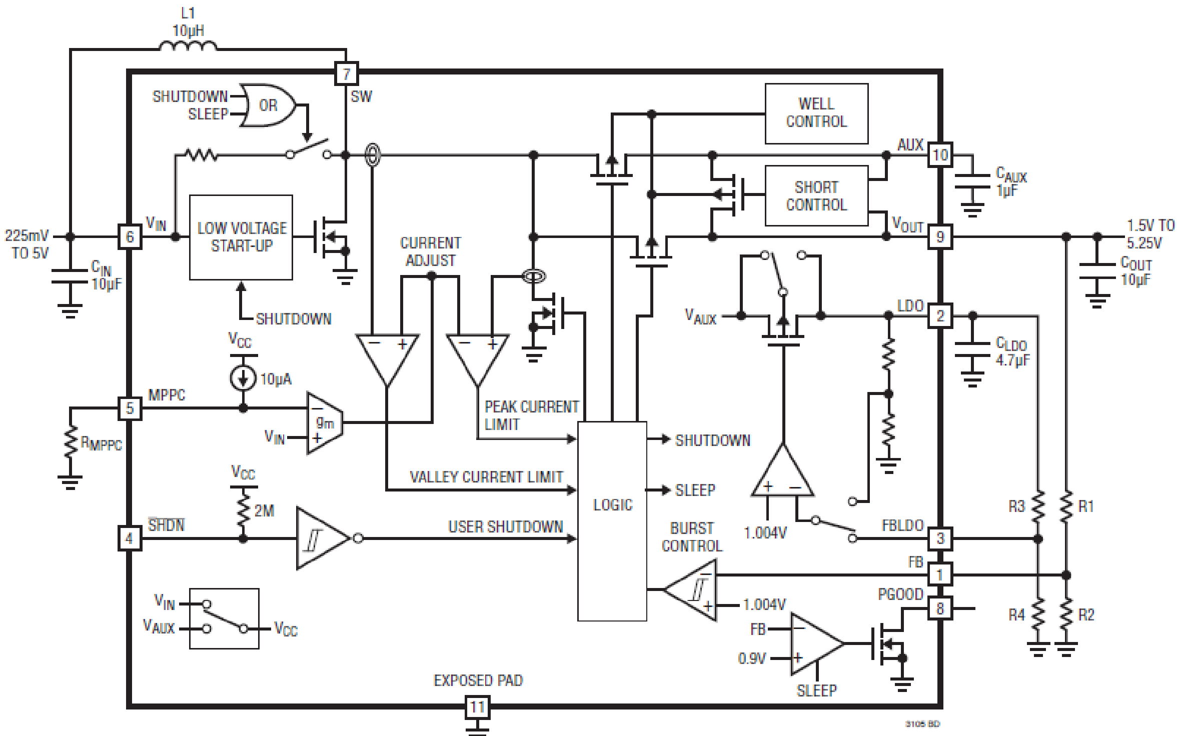


Figure 13: Internal schematic layout of the LTC3105.

LTC4070

This microcontroller from Linear Technology provides a shunt charge control while operating at 450 nA to 50 mA. It also offers a 1% float voltage accuracy across the full range of operating temperature while also reducing battery float voltage at NTC thermistor temperatures above 40 C. This offers protection for the battery so it is not damaged from overcharging and so that the LTC3105 converter cant damage the battery with higher voltage than the battery can handle (LTC3105 can convert to up to 4.35V).

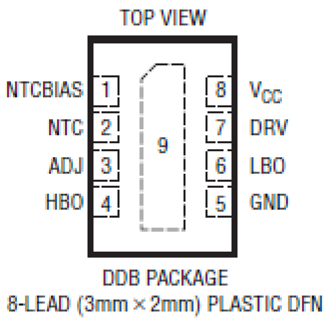


Figure 14: Top view of the LTC4070's pins.

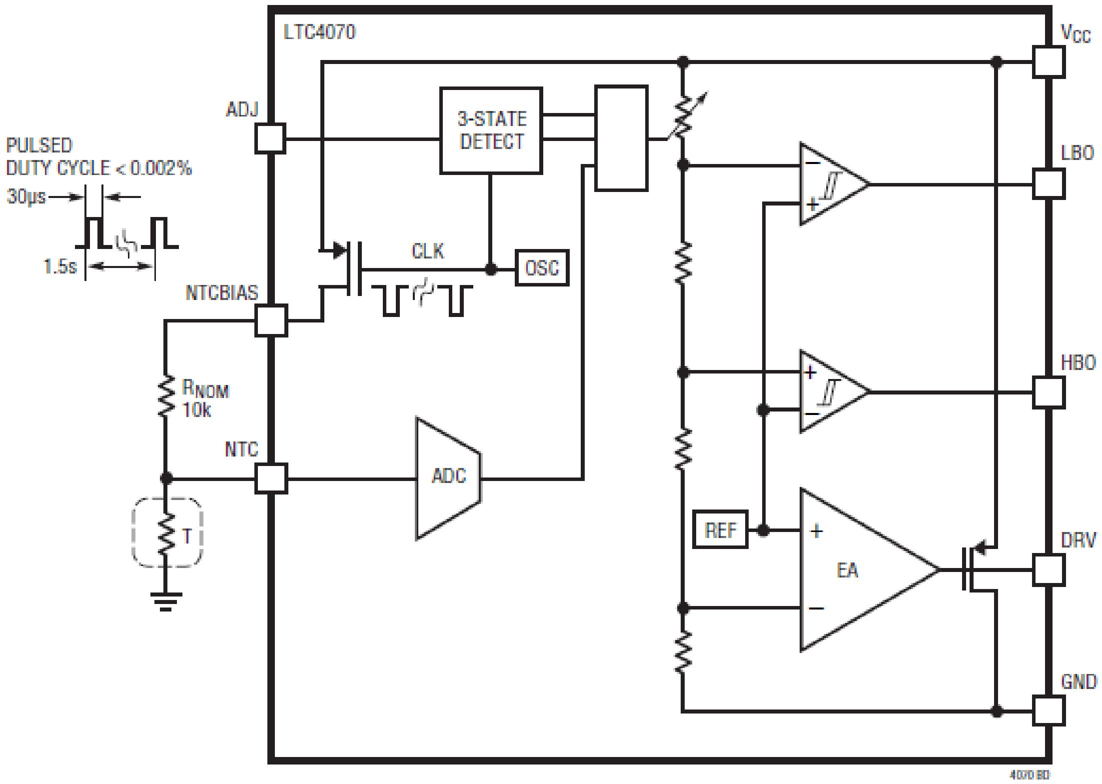


Figure 15: Internal schematic layout of the LTC4070.

Proposed Solar Harvesting Circuit

The circuit was designed within Eagle Cadsoft, a freeware PCB-design tool. The LTC3105 has a low startup voltage and even lower operating voltage, making it suitable for energy harvesting methods. It can provide a V_{out} ranging from 1.5V to 5V which is decided by the relationship $V_{Out} = 1.004 * \left(\frac{R_1}{R_2} + 1\right)$, thus covering the voltage required for recharging a large array of different rechargeable batteries[30]. In this circuit the solar cell AM-5610[31] from SANYO will be connected to PAD7 and PAD6. Whilst only being 2.5*2.0 cm^2 it can give a good indication of the least amount of energy achievable. The battery, being a rechargeable coin cell battery operating and recharging at about 3V, will be connected to PAD1 and PAD2. LDO on the LTC3105 is connected to HBO on the LTC4070 through a LED, which will be lit while the battery is charging. When the battery is full or not connected HBO>LDO and the LED will be turned off. Many of the components in between the LTC3105 and LTC4070 are chosen, as the inductance and capacitors, according to the datasheets for the microcontrollers and their values are set parameters for operational conditions of the ICs.

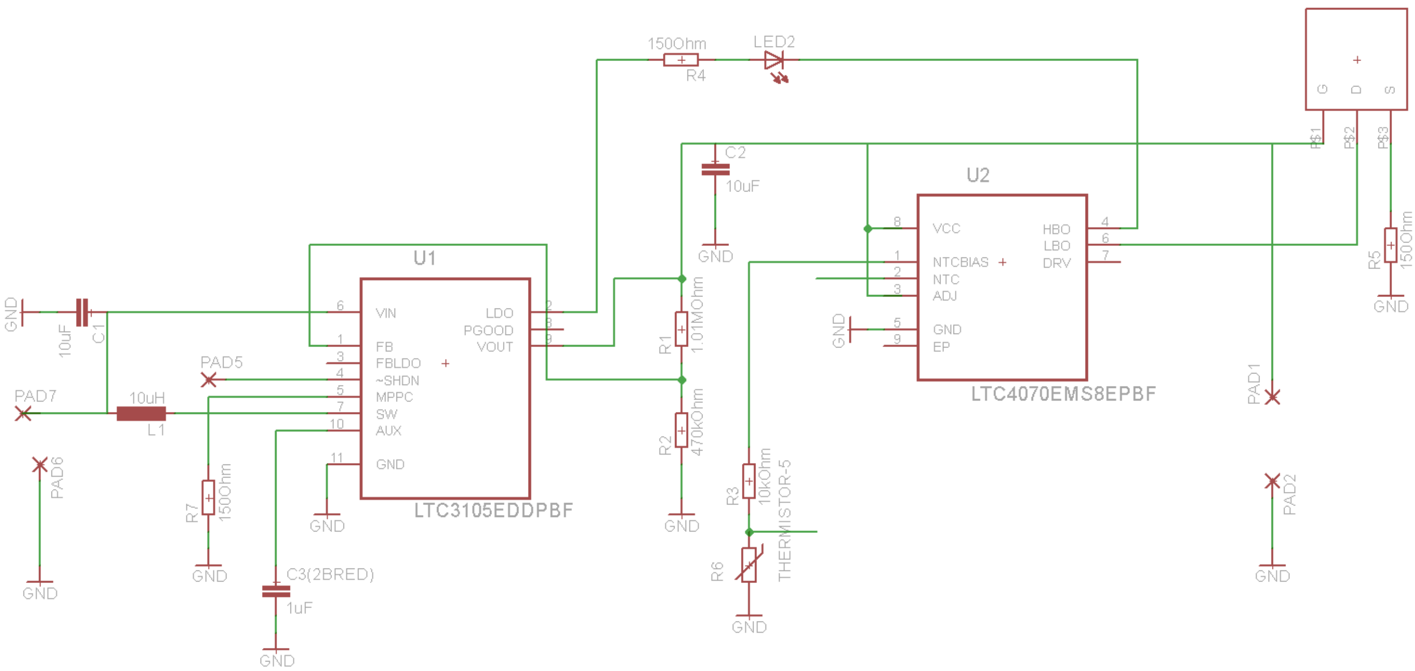


Figure 16: PCB design of the proposed energy harvester with battery protection.

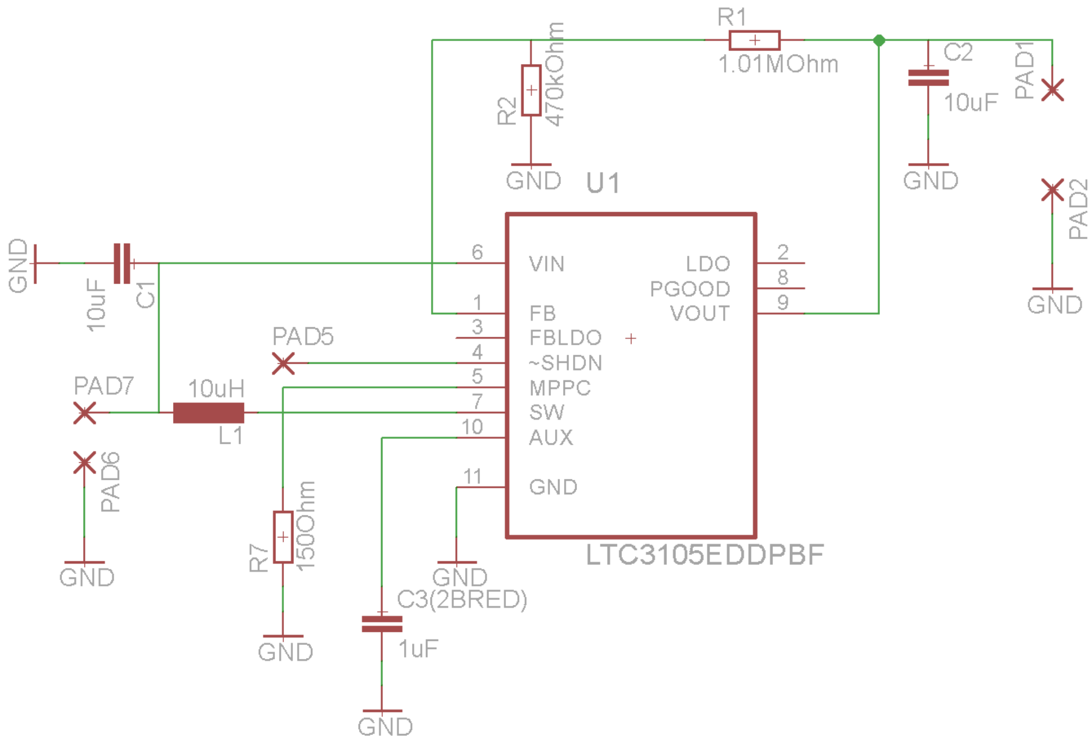


Figure 17: The LTC3105 without protection of the battery.

Result

Measurements of the LTC3105 (as proposed in **Figure** 16) together with the AM-5610 photovoltaic cell from Sanyo provided following results:

Measured Lux	Measured µW
60	8
380	34
650	48

Figure 18: Measurements done at V_{out} on the LTC3105.

These values are a mean from measuring at different inclinations of the light at the AM-5610. The power achieved is greatly affected by the inclination of light and disturbance in form of shadows and every disturbance created a unique situation that might never occur again, thus only the mean values over time were registered. According to "Arbetsmiljö-verket" in Sweden, a well-lit conference room should at least be at least 500 lux, an office where vision is of importance at 700 lux and an office where CAD is done at 500 lux[32].

As comparison, AM-5610 during optimal performance and optimal conditions:

Model	100mW/cm^2		SS-50k lux (Initial)		External dimensions (mm)	Weight (g)
	Typical operating characteristics (Initial)	Pmax (Vop-Iop)	Typical operating characteristics (Initial)	Pmax (Vop-Iop)		
AM-5610	(3.3V- 5.1mA)	18mW (3.9V- 4.6mA)	(3.3V- 2.3mA)	8mW (3.9V- 2.2mA)	25.0X 20.0	2.2

Figure 19: Characteristics for the AM-5610 photovoltaic cell from its datasheet[33]

Conclusion

The circuit presented showed to generate enough power to overcome the OLP425's power consumption while sleeping and to some further extent depending on the duty cycle. The circuit operated noticeably better when light was present compared to low-light environments and with a larger photovoltaic cell, even greater results can be achieved. It was not possible to generate enough power during low-light conditions and this is solved by either increasing the size of the solar cell or to develop the OLP425 into being more power-efficient.

Future research

Solar harvesting showed to be a possible solution for the OLP425, even with a solar cell as small as 2.5*2.0 cm^2. With the OLP425 communicating during about 850 ns, it will be in a sleep state about 99% of its lifetime if it has a duty cycle longer than 1 minute and thereby the power consumption during the sleep mode becomes its limitation. By using bigger solar cells, heavier duty cycles can be supported and with the continuous research being done on OLP425, decreasing its power consumption even further will also further open up even smaller circuit-design.

Solutions using Piezoelectronics were not investigated but if the OLP425 would be implemented on surfaces or areas that are under vibrations, this will be a lot more promising future. Piezocrystals can supply plenty with energy for an OLP425 but the major drawback is that vibrating surfaces don't come in as surplus amounts as there are for example areas luminated. Piezocrystals represent a popular area for research at present and new types of solutions surface every now and then. It is an interesting field that might develop faster than expected and is not to be overlooked, especially if ConnectBlue knows that their client will be implementing their sensors in the vicinity of kinetic energy.

Harvesting energy from ambient radio waves is an efficient method due to energy conversions and is strongly dependent on the size of the rectenna. Using ambient radio waves as a power source is still limited by the low amount of energy available in the surroundings but if microelectronics reach a breakthrough in power consumption, it might be viable. Another possible solution would be to cover a roof with several m^2 of solar panels and redirect that energy through high frequency radio waves from an antenna to all the sensor nodes, with the same principles as was used in "*Steven Percy, C. K. (2012). Supplying the Power Requirements to a Sensor Network Using Radio Frequency Power Transfer*". This way, the system will have a seamlessly endless amount of energy available due to having several m^2 gathering energy from the sun and even though the low efficiency in energy conversion, this solution might still be viable. This does however propose an entire new business model for ConnectBlue and was the main reason why it wasn't mentioned while comparing all the different solutions for supplying the OLP425 with harvested energy.

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