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PowerMod: An Open Source, Configurable Power Harvesting and Regulation Tool for Non-experts

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Abstract

We present the design, implementation, and evaluation of PowerMod, a hardware system that can harvest energy and store from low voltage, low current sources sufficient to usefully power electronics that expect battery-level voltages and currents. PowerMod has been designed to be used by developers who are *not* electrical engineers or power supply experts. The goal of PowerMod is to make it possible for typical sensor network practitioners, particularly those whose expertise lies in software, to fabricate and use power harvesting hardware in their applications. Instances of PowerMod can be fabricated from our open source design. This document serves as a user guide for the system.

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Keywords: energy harvesting, power conversion, sensor networks

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1 Introduction

Wireless sensor networks (WSNs) have a wide range of applications, and may one day be as ubiquitous as other embedded systems. We find embedded systems in nearly every aspect of modern life. As with embedded systems, an important challenge in WSNs for many applications is power. The need to power WSNs can considerably limit their scalability and hinder their deployments. Frequently changing batteries, for example, can result in maintenance being cost-prohibitive.

A WSN consists of a collection of nodes, each of which is an embedded system with a radio network interface and one or more attached sensors and/or actuators. These nodes coordinate to form a wireless network over which sensor readings, derived events, and actuation events flow. Our focus in this work is in power harvesting to support individual WSN nodes, although the hardware we developed could be useful for other embedded systems as well. There is of course a plethora of work on WSN hardware, operating systems, languages, networking, and applications. Our intent is to be orthogonal to such work to the greatest extent possible.

Our focus in this work is in power harvesting to support individual WSN nodes, although the hardware we developed could be useful for other embedded systems as well. Our specific example in this report is a Telos B mote [23], whose power demands are by nature highly variable and application-dependent. Our model is simply to collect enough energy to support mote execution for a period of time. Depending on the available power, and the power demands of the mote, it may be necessary to collect energy over several seconds or minutes to run the mote for a few milliseconds.

Numerous potential sources of power might exist in the environment of the mote. We assume an electrical source—a transducer is needed to support a non-electrical source. Our focus is on harvesting power from low voltage and low current DC or AC sources, the common outputs of such transducers, and storing it such that it can be used to run comparatively high voltage/high current devices, such as a mote. Our goal is to provide this capability to ordinary WSN practitioners, who are not electrical engineers or familiar with low voltage electronics. Transducer manufacturers sometimes publish tutorials and/or very detailed datasheets aimed to educate customers on how to implement their products.

In pursuit of this goal of bringing power harvesting to a broader community, we designed, implemented, and evaluated PowerMod, an open-source power harvesting board whose design we made publicly available[1], so that it can be fabricated by anyone. PowerMod is a configurable board that can be adjusted, via on-board switches, to be matched to various kinds of inputs.

While our target user for PowerMod is a WSN practitioner, particularly one whose specialty is in software as opposed to hardware, it could also potentially be used by domain experts who are developing an application. PowerMod could be used with some form of synthesis system that includes hardware selection, optimization [6, 5, 7, 31, 20], and perhaps together with additional hardware that supports the low-power capture of aperiodic events [13]. Configuring PowerMod requires that the prospective power source be carefully measured, but we have striven in this document to make

[1] All design files are available from our web site, `http://absynth-project.org`. These files are sufficient to have instances of the board fabricated.

the process as clear as possible. An important challenge in developing software [27] for a system powered by a power harvester is intermittent execution—the mote only turns ON when where sufficient energy has been stored and it will turn OFF again once that stored energy is depleted [4]. This challenge is outside of the scope of this paper.

Our contributions are as follows:

- We present the design of PowerMod, a configurable power harvesting board designed for WSN practitioners and advanced domain experts.
- We describe how the reader can acquire his own instance of the hardware.
- We describe the process needed to configure the hardware to harvest power from a potential source.
- We evaluate PowerMod, particularly in terms of finding the lower bounds of voltage and current at which it can operate.
- We discuss potential applications and future research.

This paper begins by taking the perspective of the target user, a WSN practitioner or advanced domain expert. Section 2 gives an example application and its potential localized source of power. This is followed in Section 3 by a discussion of other potential power sources that are well known in the literature, but may not be on the target user's radar screen. Next, Section 4 is a user manual for PowerMod, while Section 5 is a tutorial for its use.

We then shift our perspective, and consider the PowerMod system itself. Section 6 describes its design and implementation, while Section 7 evaluates the limits on input voltages and currents necessary to activate PowerMod. Section 8 describes related work, and Section 9 concludes.

Beyond this decomposition of the paper into two perspectives, our presentation attempts to shield the WSN practitioner or advanced domain expert from unnecessary detail. Where details are needed in the main text, we include "Plain English" sidebars. Where details are not needed but may be interesting, we include "Advanced" sidebars, and example of which follows.

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What can be powered using this technology?
The ubiquity of embedded devices is largely constrained by their need for power. Fortunately, the power requirements have been minimized to the point that microcontrollers are available that consume in the order of nano-watts, and overall power is carefully managed.

A new breed of microcontrollers have achieved extremely low power consumption due to advances in silicon processing advances and specialized architectural features. Transistors get more efficient as new materials and processing techniques are found. Computer architecture and circuit designs have added features that allows microprocessors to consume less energy when in sleep mode. For example, some architectures distribute power to the individual blocks only when needed; and, to minimize power consumption each voltage is kept at the block's minimum operating voltage.

Other embedded components, such as transceivers used for wireless communication and sensors often have different power requirements than the microcontroller. Over recent years these components have significantly reduced their power needs. In fact, it could be said that power management has impacted nearly every electronic component. Processing technologies and new materials make it possible to produce very efficient components.

Complete embedded devices often have multiple voltage rails and power requirements. PowerMod offers three voltage sources with different characteristics, and also includes an enable signal that enables external power management.

2 Example

Consider building a sensor network with the goal of monitoring the structural integrity of a bridge [15]. A node might, for example, monitor a crack or other flaw with the goal of sending an alert message should the flaw change considerably over a short period of time. These messages would allow bridge maintenance efforts to be carefully focused so as to maximize safety. Many hundreds of WSN nodes might be needed, and these could easily be placed in out-of-the-way locations.

How can we power these nodes? While a low power mote, such as the Telos B is probably sufficient for the application, these are normally powered via rechargeable or non-rechargeable batteries. While the bridge may well have electrical power infrastructure that could be tapped to provide a long-term source, this would in many cases obviate the point of having the monitoring network be wireless in the first place, as well as produce the maintenance headache of electrical wiring leading to difficult to access locations on the bridge.

One alternative is to periodically replace or change the batteries. However, this produces its own maintenance headaches, especially if the network has many nodes. We would expect the number

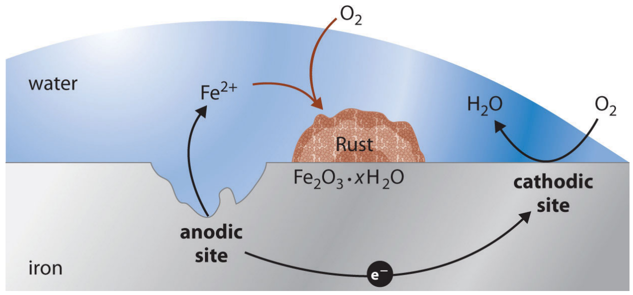


Figure 1: Illustration of the creation of rust

of nodes to grow with the size of the bridge and its level of disrepair. While the battery costs might be low, the labor costs would be considerable, again obviating the point of having the network in the first place.

A possible solution for a long-term and/or large-scale deployment is to extract the needed power from its environment. There are many ways in which this might be accomplished, and the materials and technologies underlying transducers that can transform power in one form into electrical power has matured tremendously, and this is likely to continue. Current research on "power harvesting" is active and spans many fields, as we describe in more detail in Section 8. Application whose goal is to inexpensively monitor the structural integrity of a bridge [15]. A node might, for example, monitor a crack or other flaw with the goal of sending an alert message should the flaw change considerably over a short period of time. These messages would allow bridge maintenance efforts to be carefully focused to maximize safety.

An important appeal for power harvesting is that, unlike the previous alternatives, the power cost becomes a part of the fixed cost of the sensor network system—the transducer and power conversion hardware is integrated into the WSN node and deployed along with it. If sufficient energy is available, the node can then be ignored until hardware failure occurs. The variable cost of the sensor network is limited to the maintenance required by hardware failure.

The power of corrosion: To make this discussion more specific, consider rust, which is surely present on a decaying iron bridge. The corrosion of metals is a chemical process called oxidation-reduction. When iron rusts, we can also say that it corrodes or oxidizes. In oxidation, metal molecules shed electrons while they prepare to combine with oxygen to form metal oxide. The shedding occurs in material referred to as an anode, while the combination occurs in material referred to as a cathode.

$$Fe + O_2 \rightarrow Fe_2O_3, \tag{1}$$

this is is a two step process. At the anode positively charged iron ions, and electrons are produced:

$$Fe_{solid} \rightarrow Fe^{+2} + 2e^{-}.$$

Simultaneously, at the cathode we have

$$O_{2gas} + 2H_2O_{liqud} + 4e^- \rightarrow 4OH^-_{aqueous}.$$

Rust is finally formed when

$$4Fe(OH)_{2solid} + O_{2gas} \rightarrow 2Fe_2O_3 \cdot H_2O_{solid} + 2H_2O_{liqud}.$$

If electrons shed by the metal at the anode are allowed to flow to the cathode where they are used, this current constitutes a power source. The voltage differential between anode and cathode is a function of the metals involved and as well as how easily they give up electrons. The current would largely depend on the size of the anode and cathode areas. Tables of "standard reduction potentials" shows the that the oxidation of iron can yield -0.44V.

This potential power source is essentially the dual of the commonly used rust reduction approaches in which electrons are provided to the cathodic reaction before the anodic reaction can supply them. Figure 1 illustrates the chemical reaction that takes place to form rust. The most common method of adding electrons is to use a metal that sheds electrons faster; metals such as zinc or magnesium. These *galvanic* metals add zinc as a sacrificial metal so it can corrode instead of the metal structure. In fact, the oxidation of zinc produces more free electrons. Another approach simply provides the electrons from an electrical source such as a battery.

For reasonably sized, ungrounded anode and cathode areas, the available current would be very small. If we connected these areas through our mote's battery terminals, nothing would happen. What is needed is a circuit that is able to take the tiny voltage differential and very low current and use it to charge up a storage component that can then be used to provide comparatively higher voltage and current to the mote, albeit only until it discharges. A long charge period during which the mote would be dormant would be followed by a short periods in which the mote would be active.[2]

Using the techniques we elaborate on in Section 4 and Section 5, we measured a bridge in the Wilmette, Illinois area, shown in Figure 2. The bridge is made up of sections of *iron* grating that are approximately 25 pounds per square foot. We can use this information to estimate what the voltage and current would be, using reaction chemistry described above.

We took electrical measurements from the bridge using the schematic of Figure 3, finding that

$$Voltage = 0.33\,\mathrm{VDC}$$

$$Current = 130\,\mu\mathrm{A}$$

which coincide with the expected values when calculated using data from the "Handbook of Batteries" [10].

[2]We use a simplified terminology here. In actuality, the reaction produces a very small voltage difference, and the anode and cathode themselves have a small internal resistances that limits current. Additionally, the conversion component will not be 100 % efficient, and the storage component (a capacitor) will also leak or dissipate energy. The available power from the oxidation-reduction process must exceed the losses in conversion and storage for the system to work at all.

Figure 2: Photos of the evaluated bridge.

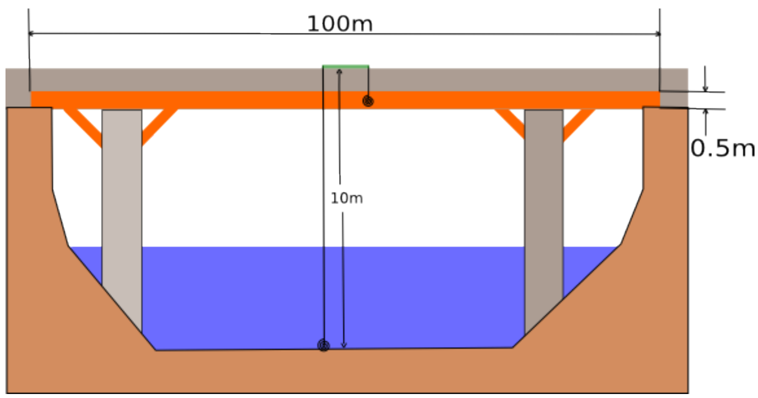


Figure 3: Schematic for bridge measurements.

These measurements represent the direct current (DC) characteristics, which we interpret as being due to the rust reaction. We also measured the alternating current (AC) component in order to get the full picture of what energy might be available. Figure 4 illustrates that AC voltage is also available, with peak frequencies as shown in Figure 5. Our interpretation is that this comprises RF energy being captured by the bridge acting as an antenna, although we cannot explain why these peaks should occur.

Note that both the AC and DC measurements are of very small signals. A Telos B mote requires a 3 V source at 25 mA to supply the microcontroller and receive transmit messages. Hardware that provides conversion and storage is essential to being able to tap this power source at all. The goal of PowerMod is to provide precisely this conversion and storage functionality.

3 Other environmental power sources

We now consider some common power harvesting sources, with additional purposes helping the reader gain some perspective on how to think about harvesting power.

Energy may be available in different forms. A *transducer* is used to convert energy from one type

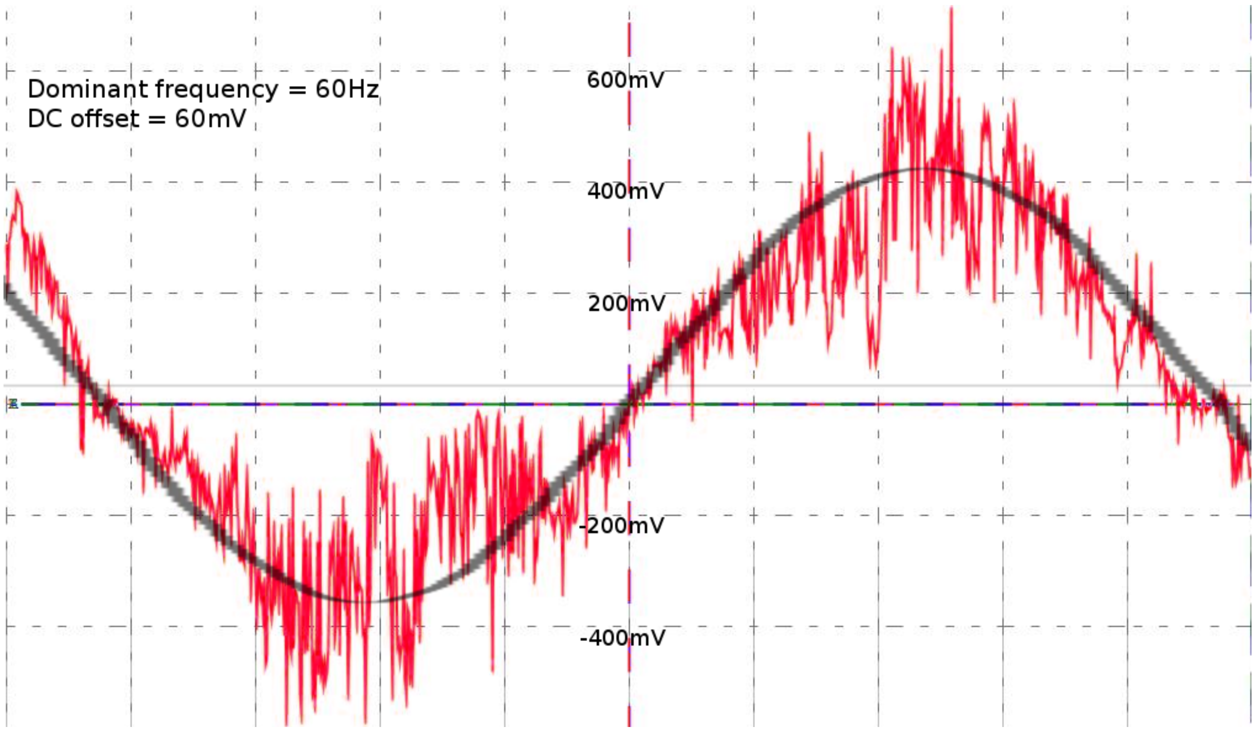


Figure 4: AC measurements of bridge

to another. For harvesting applications, transducers are used to convert to electrical energy from other types of energy. Types of energy include, chemical, mechanical, electromagnetic (i.e. light), and thermal. PowerMod and other tools like it can then convert this electrical energy into a suitable form and store it. Survey papers are available that compare the various sources of power [25].

We now describe three sources in more detail, light sources (e.g., solar), thermal sources, and mechanical sources. Transducers for such sources can be ordered from companies such as Digikey and Mouser.

3.1 Light

Solar energy, and in fact any light source can serve as a source of power. Solar cells (or panels) are transducers that convert light energy into electricity. Solar cells are flat sheets of a dark material that is often sandwiched between sheets of glass. Cells can vary dramatically in cost and efficiency of conversion. Because the power available from a cell may be insufficient, it is common to connect cells in parallel or series to achieve the needed voltage and current characteristics.

Light can be thought of as consisting of particles called photons. When these photons strike the semiconductor material of the solar cell, they knock off electrons that are the basis of the electrical current of the cell. Light can also thought of as a traveling wave which has an associated frequency (or wavelength).

Solar cells respond to visible light but also include wavelengths in the range of ultra-violet and

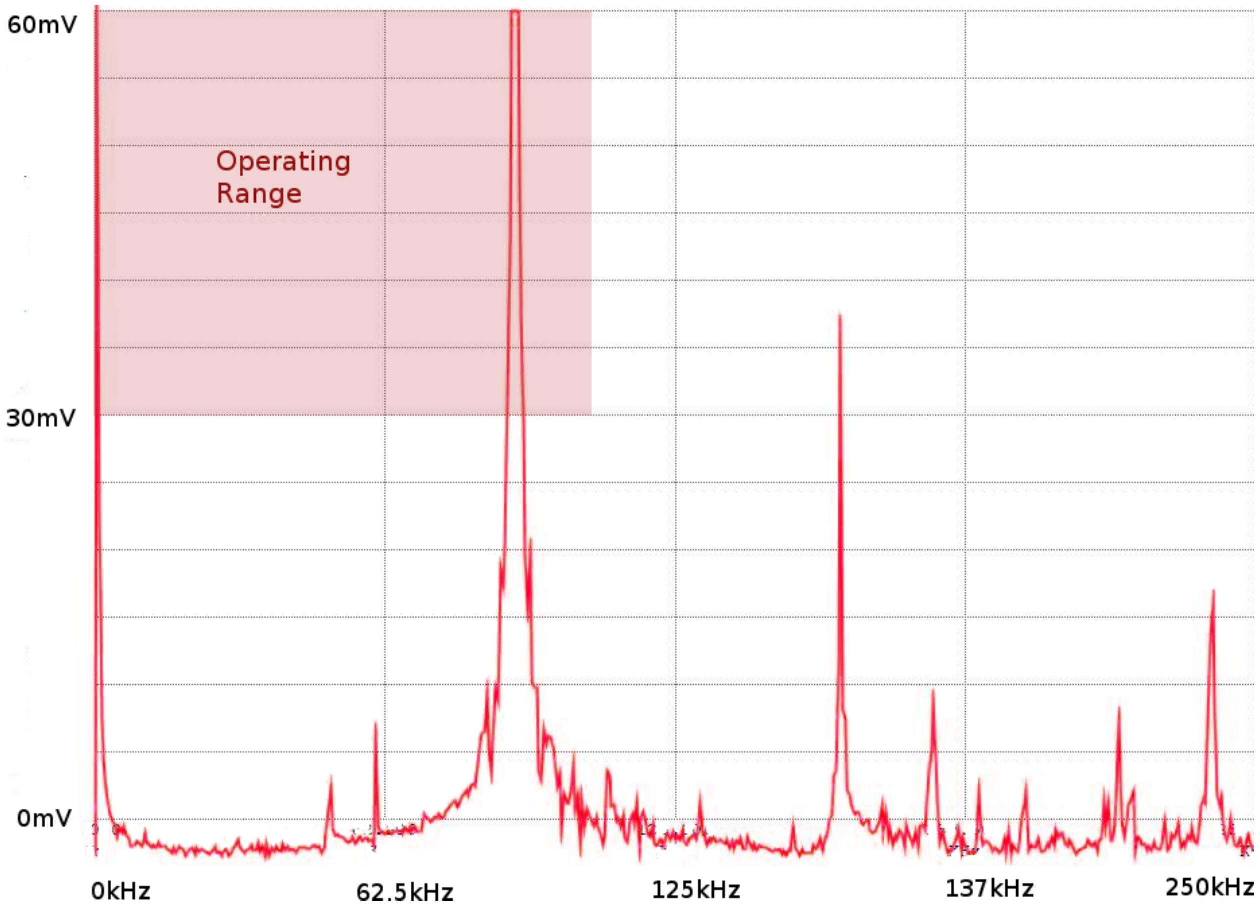


Figure 5: Frequency measurements of bridge

infrared. Solar cells have an optimal operating wavelength, at which they most efficiently convert light to electricity, and is quoted in the datasheet. It is common for the optimal range to tend to the infrared region.

From a practical point of view, many commercial solar cells are readily available and can be incorporated into a project. We used the solar cell (model 276-124) component from Radio Shack because it is small, simple, and produces enough energy for our purposes. Radio Shack sells this for $5 and it produces up to 0.5 V and 200 mA.

3.2 Heat

It is possible to extract energy directly from heat. Transducers called ***Peltier*** components (or thermo-electric generators (TEGs)) exist that directly convert temperature differentials into electricity. Implementing this form of power harvesting is fortunately very straightforward.

A TEG is basically a ceramic plate with two wires. Electricity is generated when heat flows from one face of the plate to the other. In other words, when one side of the plate is hot and the other side is cold and heat flows through the plate from the hot side to the cold side, current flows from

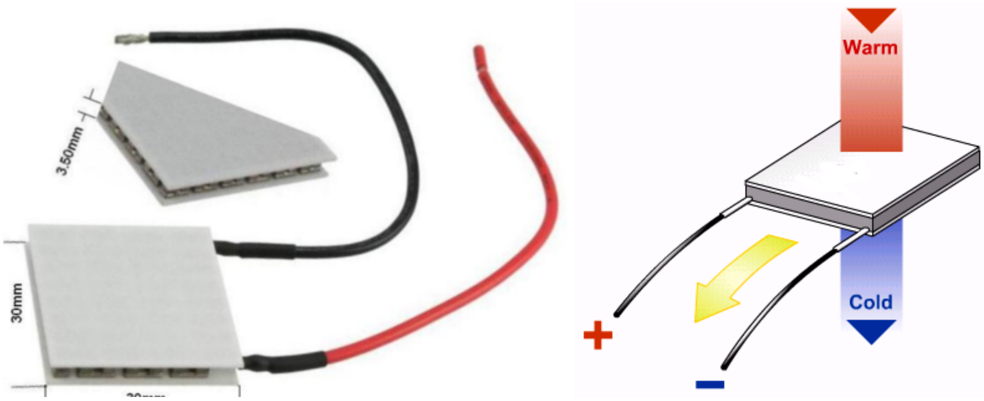


Figure 6: Peltier / TEG device

one wire to the other. If the direction of the heat flow is reversed, the current flow also reverses. The generator be used to convert a current flow into a heat flow.

The voltage generated by a TEG is proportional to the difference in temperature between the faces of the plate. In an application where a TEG is used to take advantage of environmental temperature variation, the interface electronics (e.g., like PowerMod) need to take this into account.

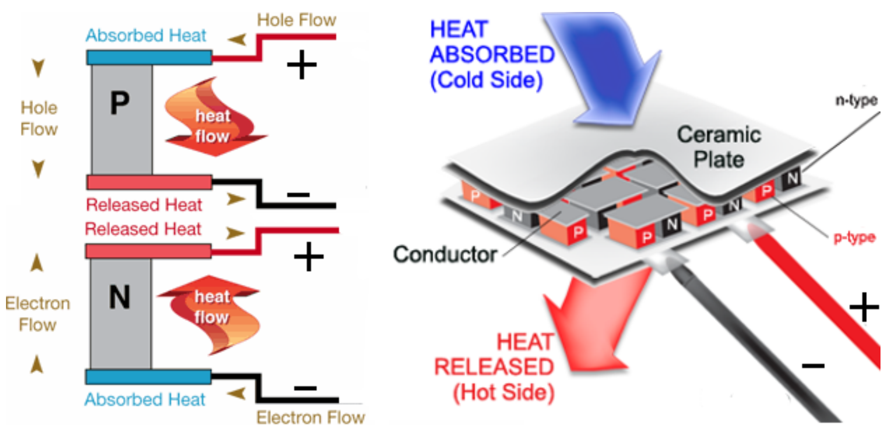
The electrical power produced by a TEG is proportional to the area of the plate. The main difference in different TEG models is how efficient the conversion process is, with manufacturers vying to produce as much electricity per square inch as they can. There are also some limitations on the materials used that will shift the temperatures that the components will work well in.

From a practical point of view, commercial TEGs are readily available and can be incorporated in to a project. TEGs are can be found in most parts stores such as *Digikey*, *Mouser*, and even *Amazon*. TEGs can be found by searching for the keyword *Peltier*. We evaluated the ZT8,12,F1,4040, ZT Series components from Laird Technologies.

Advanced

A TEG is an application of the Peltier and Seebeck effects. Without going into much detail into the theory, we offer an abbreviated introduction.

The TEG is basically N and P type semiconductors coupled together and sandwiched between ceramic plates. The ceramic plates are there just to distribute the heat and provide structural integrity.



Semiconductor components can be mixed (doped) with other materials to produce new materials that either have extra electrons (N type) or are missing electrons (P type). It is from the properties that arise from the disparity of these new materials that an electric current is induced perpendicular to the flow of thermal energy. Current research has had success using properties of carbon nanotubes to increase the efficiency of this type of energy transformation.

The relevant equations for thermoelectric (Peltier) components are

$$
\begin{aligned}
Th &= Tamb + (^{\mathrm{C}}/_{\mathrm{w}})(Qh) \\
Qh &= Pin + Qc \\
dT &= Th - Tc
\end{aligned}
$$

where

Th	Hot side temperature
$Tamb$	Ambient temperature inside the system's case
C/W	Heatsink efficiency ($^{\mathrm{deg\ C}}/_{\mathrm{Watts}}$)
Qh	Total heatsink load (Watts)
Pin	Power input (Watts)
Qc	CPU heat load (Watts)
dT	Temperature difference between cold and hot sides
Tc	Cold side temperature

Material	**Thermal Conductivity** ($^{W}/_{m}/_{K}$)
Silver	406
Copper	385
Brass	109
Aluminum	205
Steel	50.2
Lead	34.7
Mercury	8.3
Ice	1.6
Glass,ordinary	0.8
Concrete	0.8
Fiberglass	0.04
Brick,insulating	0.15
Brick, red	0.6
Cork board	0.04
Wool felt	0.04
Rock wool	0.04
Styrofoam	0.01
Wood	0.12–0.04
Air at 0 degC	0.024

Figure 7: Thermal Conductivity Table

In practice the goal is to keep one side as hot as possible while keeping the other side as cold as possible. A possible way of doing this is to use an insulator around the TEG so heat does not move except through the TEG. It is also common to connect the surfaces of the TEG to radiators (fins) that increase the surface area, or copper heat pipes. Connections between the TEG and other materials should be coated with a thermal interface material that maximizes heat transfers. A popular commercial product is called *Artic Silver*. Finally, another common configuration for TEGs is attaching a side to a liquid flow box.

Since a TEG implementation requires heat flow management it is useful to know how well different materials conduct heat. This property of materials is captured in ***thermal conductivity tables***. Figure 7: shows the thermal conductivity of some common materials[3]; larger tables exist. Note that the conductivities of materials is dependent on their temperature.

It is surprising how common TEGs have become. NASA uses TEGs to power the Mars rover ”Curiosity” with a nuclear material as the heat source.[4] BioLite[5] uses TEGs connected to a camping stove to recharge the batteries of hand-held devices.

[3] `http://en.wikipedia.org/wiki/List_of_thermal_conductivities`
[4] `http://nuclear.gov/pdfFiles/MMRTG.pdf`
[5] `http://biolitestove.com/`

3.3 Motion

There are numerous ways we can harvest energy from movement, of which we describe two here.

Alternators or *generators* employ the Faraday effect by rotating a shaft on which are affixed magnets near a wire coil (or vice-versa). The movement of the magnetic field induces a perpendicular electric field. The result is that mechanical power is converted to electrical power. The mechanical power that rotates the shaft may have many different sources.

Although generators are used for large scale electrical power generation, compact components exist, such as small commercial turbine designed for harvesting power from the water motion in a river.[6]

Piezoelectric materials are used to create transducers that convert mechanical excitation, such as compression, expansion, and torsion, into electrical impulses, or vice versa. A common example, is the quartz crystal used in a clock, which mechanically oscillates at a known frequency given an electrical input. If the quartz crystal were instead mechanically excited, it would produce electricity. There are many other materials that exhibit this behavior.

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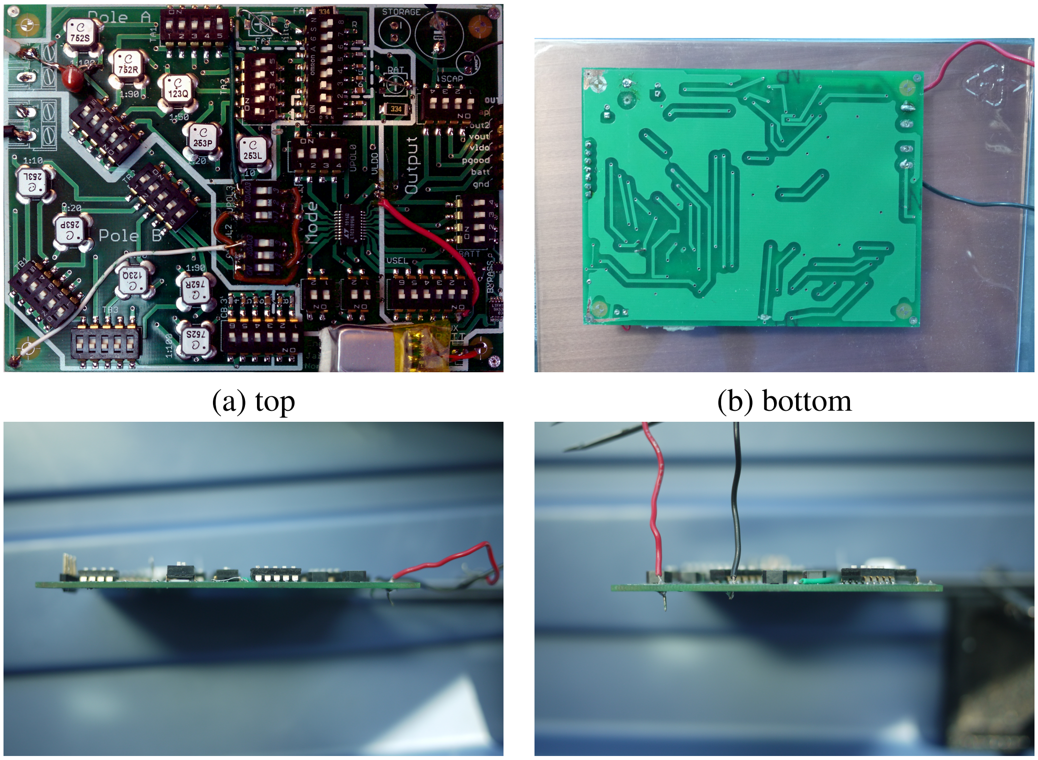
A promising new family of mechanical transducers are those based on *Electroactive Polymers (EAPs)*. EAPs are man-made materials that interact with electric fields (applied or produced). An example of these are the *dielectric elastomer*, which are elastic materials that produce an electric current when they are stretched.

4 User manual

Many of the numerous conceivable sources of environmental energy, such as those described in Sections 2 and 3, share a common trait: the electrical power produced by their transducers is weak and/or not at the voltage and current level needed to power a mote. A typical mote expects a stable, DC supply at a given voltage and current. The goal of PowerMod is to make it easy to bridge this gap between the attributes of the transducer and its environmental source, and the needs of the mote or other electronics that need to be powered. It does this by a process of electrical conversion and electrical energy storage.

PowerMod must be tuned to the requirements of both the transducer and the target electronics. It has been designed to be readily configurable using switches. A configured PowerMod may then be incorporated in to a design, or the configuration data could be used to produce a customized PowerMod that is more compact. The heart of PowerMod is a commercial power harvesting chip which is quite tiny, so the final harvester for a particular can be built to be physically much smaller

[6] `http://www.coroflot.com/hulld/vena-microhydro-system`



(a) top (b) bottom

(c) long side (d) short side

Figure 8: PowerModboard from every angle.

than the highly configurable PowerMod board. The chip is 0.24 x 0.34 inches and the entire PowerMod board is 3 x 4 inches.

The purpose of this section is to act as a user guide that introduces PowerMod , explains how to get a own copy of it, and explains how to configure it for a given transducer and mote.

4.1 The PowerMod board and how to get a copy

Figure 8 shows multiple views of the prototype PowerMod board. The pictures show assorted alterations (patch wires and trace cuts) that we made during testing. The final board design is physically almost identical, except that there are no patch wires or trace cuts.

The PowerMod design documents are available from the ABSYNTH Project web site.[7] The design documents are open-source, distributed with the four-clause BSD license. The important elements of these are the printed circuit board (PCB) layout, the parts list, and parts placement information. While such documents may seem quite daunting if one is unfamiliar with hardware design, they make the several things straightforward, as explained below.

[7] `http://absynth-project.org`

Complete fabrication: Simply by sending these files to an appropriate fabrication shop (and there are many), one can order completely built PowerMod copies. By "completely built", we mean that the shop will return a ready-to-use PowerMod as in Figure 8. This will include "board fabrication" (making the printed circuit board and drilling the relevant holes in them), "board stuffing" (putting the components into the board), and "soldering" (permanently affixing the components in an electrically stable way). In our experience, in Chicago, the cost of getting a PowerMod made, in quantity one, with a 2 week turnaround, is $300. The pricing has a fixed cost (basically, the setup to make any number of boards), and a per-board cost, which declines with more boards.

Partial fabrication: For a lower cost, one can limit the "board fabrication" stage, in which case the shop will return an etched and drilled PCBs with no components attached. The components can be manually mounted, or partially build by fabricator. Note that much of the board involves surface mount components, and some can be challenging to solder in by hand. Depending on the application, a possible alternative is to only install the components needed to fine tune the PowerMod.

Experimentation: The design documents include the schematic and PCB layout in industry-standard forms, as well as Eagle CAD files. The PowerMod design is described in more detail in Section 6.

We used the following vendors for components and fabrication:

- Digikey for most parts
- Mouser for power transistors
- Coilcraft for transformers
- Fine Circuits for board fabrication and assembly

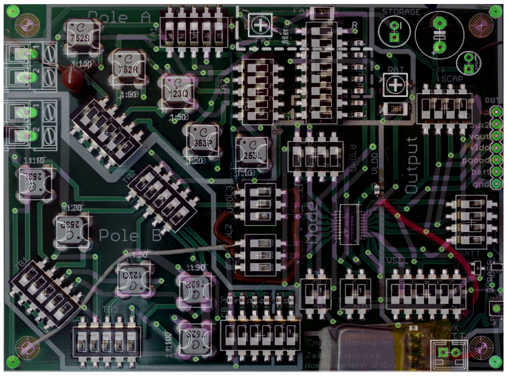
A detailed parts list is included with the distributed design.

4.2 Understanding the PowerMod board as a user

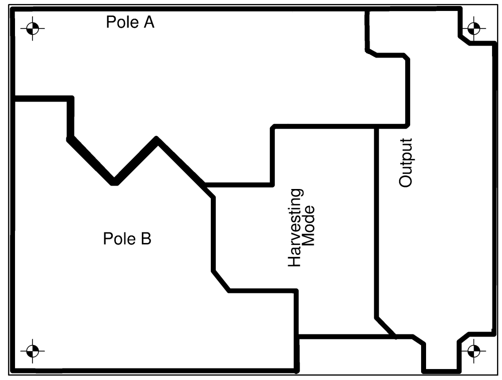
PowerMod is basically a power harvesting system, complete with electrical conversion and storage on a single board. As such, it is unavoidable that the board be populated with various components that are needed for the different applications. Not all components may be needed by the application.

In order to work with PowerMod it is important to be familiar with the board's blocks, and the appearance of particular components. Figure 9 illustrates these elements. Figure 9(a) shows a photographic view of the top of the board, where all the configurable elements reside, and where all connections are made.

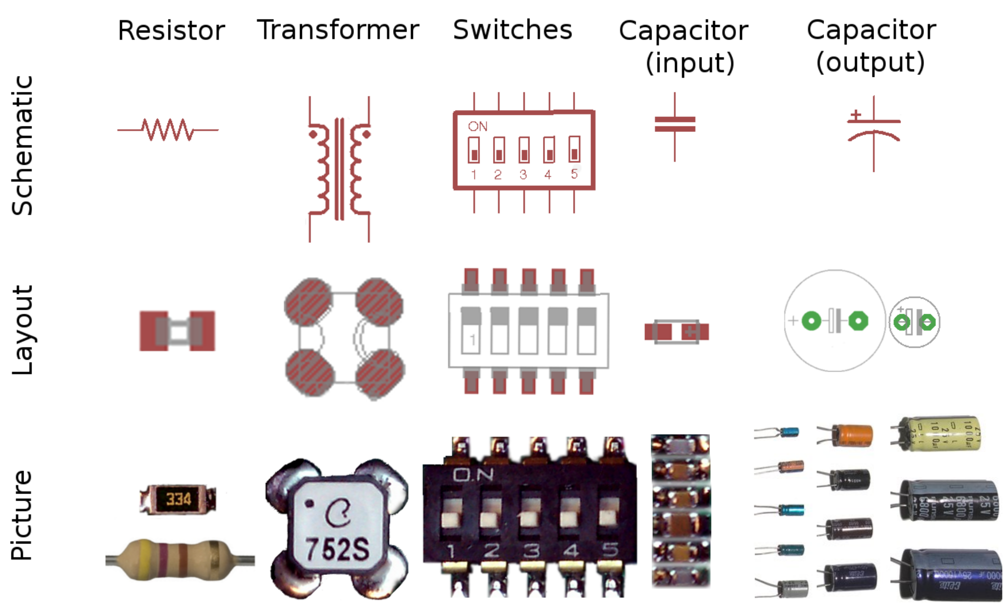
Figure 9(b) shows the major blocks (or sections) of the PowerMod circuit, which we will refer to in the remainder of this document. The board is divided into four blocks, *Pole A*, *Pole B*,



(a) Top View (Photo)



(b) Top View (Diagram)



(c) Component reference

Figure 9: Understanding the PowerMod board: (a) photo, (b) block diagram, (c) components and their representations.

Harvesting Mode, and *Output*. Pole A and Pole B are input blocks that are separately configurable to support the two possible polarities of the input voltage with respect to ground. The Harvesting Mode block allows further configuration with respect to input characteristics, and also contains the power harvesting IC that the PowerMod is based on. Proper Configuration of Pole A, Pole B, and the Harvesting Mode blocks matches the IC to the input such that its conversion process operates with maximum efficiency. The Output block allows the IC output characteristics to be matched to the input needs of the client device. The Output block also contains storage for accumulating energy, making it possible to store enough energy to run a device for short periods of time that cannot be run continuously because there is insufficient power available from the input device.

Figure 9(c) lists the important kinds of electronic components that exist on the board, showing, for each one, a picture, their block representation on the PCB layout, and their representation on an electronic schematic diagram. Most importantly, the board is populated with numerous arrays of switches ("Dual Inline Package Switches" or DIP switches). Almost all of the configuration of the PowerMod board is determined by the settings of these switches. The switches are enumerated starting with switch number *1*, which is marked on both the schematic and the real hardware. All the switches in the schematic are shown in the ON position, marked in black.

The final design implements some of the wired changes seen on the picture.

4.3 Input characterization

PowerMod must be configured to match the input characteristics of the transducer and source. Without this matching, it will work sub-optimally, and perhaps not at all.

Input characteristics comprise the available power, the voltage, the current, polarity, and the behavior of the voltage (DC, AC, or both). To measure these properties, it is possible to use a basic multimeter, but an oscilloscope is ideal. A simple, inexpensive pocket oscilloscope such as a DSO Nano is sufficient in many cases. It is helpful, but not essential for the oscilloscope or meter to have PC connectivity—we had good results with a Link Instruments MSO-19.2 USB oscilloscope. Both of these oscilloscopes cost less than $200.

We describe how to measure current and voltage in more detail in Section 5.

What are power and energy?: *Power* is the rate at which energy is consumed. In an electrical sense, *instantaneous power* is given by equation 2. This equation gives us the amount of power that a device consumes at any given instant.

$$Power = Voltage \times Current \tag{2}$$

Power is needed to perform a task, but tasks take time, hence equation 3. *Energy* is can be transformed into other types of energy.

$$Energy = Power \times Time \tag{3}$$

We can use this equation to figure out how much energy we need to harvest and store to power our device. For example, if we have a device that uses 50 mW of power, and needs 100 milliseconds to complete a task, then we must harvest and store 50 mW × 100 ms = 5 mJ of energy to accomplish the task. This example is similar to what a Telos B would require to take a temperature and communicate its findings.

We can consider the harvesting and storage task in a similar manner, the available power is determined by the voltage and current of the source, while the time needed to run the task depends on the amount of energy the device needs to have stored to run its task. Suppose the input source is has voltage 100 mV and current 10 µA. Then it we can harvest at most 1 µW of power from it. At this rate, storing 5 mJ will require at least 5 $^{\mathrm{mJ}}/_{\mu\mathrm{W}}$ = 5000 seconds, or about 1.3 hours.

Important characteristics of voltage: Conceptually, the source transducer has two wires that will attach to input pins of PowerMod. The expected behavior of the voltage across these wires determines most of the configuration. We will refer to them as A and B.

First, we must know the polarity. The polarity is simply whether A is positive with respect to B or the opposite. It possible for the source to alternate polarity as well (multipolar). PowerMod can support unipolar positive or multipolar sources.

Second, we must know whether the voltage is DC, AC, or both. DC means that the voltage is constant and does not change in time. AC means that it varies across time periodically and deterministically. In this paper however, we use the term AC to refer to any time-varying signal. Note that a multipolar source contains AC, but an AC source need not be multipolar. In other words, multipolar only applies when voltages can change polarity from positive to negative and vice-versa.

Third, we need to know the voltage of the source. The long-term average voltage is the DC component of the voltage. The difference between the maximum voltage and the minimal voltage is the peak-to-peak voltage characterizes the AC component.

Finally, for sources with a significant AC component, if it has dominant frequencies, it is helpful to know them. If using an oscilloscope or spectrum analyzer, the frequencies can be picked out using a frequency domain view (often labeled as FFT).

Considering Figures 4 and 5, which are screen captures from oscilloscope, we see the source is multipolar, has a DC component of about 0.33 V, and a 1 Vpeak-to-peak AC component with dominant frequencies of 60 Hz and about 100 kHz.

Short circuit: If the power source were to short circuit, the PowerMod would see a low resistance and high current at its inputs. The high current could damage the bard. It is possible to protect the board from such damage by using the *high current* option. Note however that adding this protection will increase the efficiency and the minimum voltage that can be harvested.

4.4 Harvesting mode configuration

Once the input voltage and current characterization has been done, the next step is to configure the harvesting mode block, shown in Figure 10. The two harvesting modes are

- Multipolar, and
- Unipolar.

Not surprisingly, these mirror the input voltage characterization from Section 4.3.

Strictly speaking, PowerMod has two channels *Pol A* and *Pol B*. Each channel is configured independently. Or, in the *unipolar* case both channels are tied together and the configuration is done

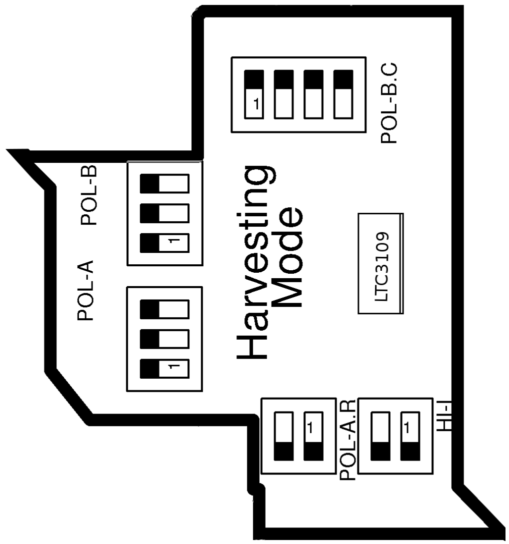


Figure 10: Harvesting Modes

	Switch			
Switch Block	**1**	**2**	**3**	**4**
POL-A	Bi	Uni	Uni	
POL-A.R	Uni	Bi		
POL-B	Bi	Bi	Uni	
POL-B.C	Bi	Uni	Bi	Uni

Figure 11: Configuring polarity

from *Pol A*. Figure 11 illustrates the switch settings needed to choose between unipolar and multipolar operation. To configure for unipolar operation, set all switches marked “Bi” on, and the others off. To configure for unipolar operation, set all switches marked “Uni” on, and the others off.

Pol A has additional signal conditioning options. It is capable of working with high current sources. Any input that exceeds the operational maximum is automatically grounded, offering ***over-current*** protection. This comes at the cost of lower power conversion efficiency. Figure 12 shows how to set the switches to choose between normal and high-current operation.

HI	**High-current**	**Normal**
1	OFF	ON
2	ON	OFF

Figure 12: Configuration for high current protection

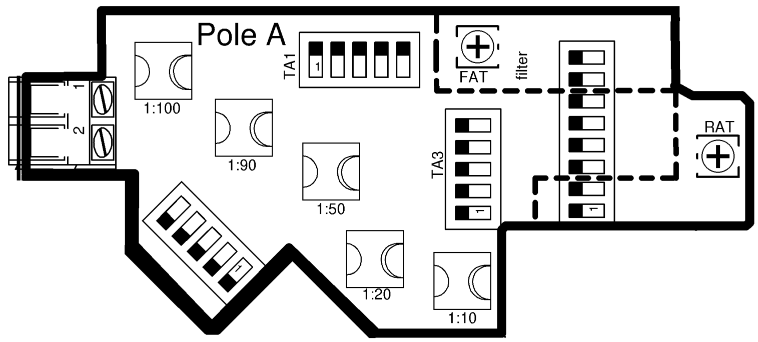


Figure 13: Pole A

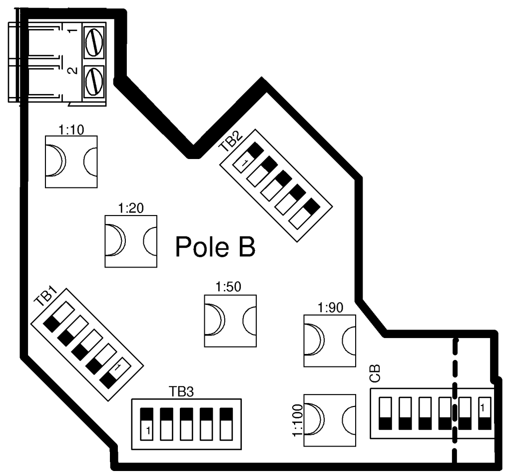


Figure 14: Pole B

4.5 Pole A and pole B input configuration

Figures 13 and 14 show the Pole A and Pole B blocks of PowerMod, illustrating the locations of the configuration switches. The chip on which PowerMod is based operates best with an input signal that oscillates at a frequency between 10 kHz and 100 kHz and a peak-to-peak voltage of 30 mV to 6 V. It is important to understand that even if the input is pure DC, the chip and the circuitry on PowerMod will *create* this oscillatory signal. The configuration switches on Pole A and Pole B tune the frequency of oscillation and the degree to which the input voltage is increased. The goal of configuring Pole A and B is to get the input the chip sees to within the "sweet spot" range given above.

The input signal is manipulated using a combination of transformers and capacitors. The inductance (in the transformer) and capacitance, combined with switching on the chip, produce oscillations. The turn ratio of the transformers determines the degree to which the voltage is scaled. It is possible to calculate exactly what the turn ratio and capacitance should be, but this requires a more complex electrical model of the source than we explained so far, and it requires a similarly complex model of the input load of the chip. We generally found that experimentally determining the values is easier in practice, and the board is designed to facilitate this.

Turn ratio	TA1 / TB1	TA2 / TB2	TA3 / TB3
1:100	1	5	5
1:90	2	4	4
1:50	3	3	3
1:20	4	2	2
1:10	5	1	1

Figure 15: Configuring transformer turn ratio via switches 1, 2 and 3 for poles A and B

Switches	C1A [nF]	C2A [nF]
1	-	1
2	-	0.47
3	33	-
4	10	-
5	4.7	-
6	1	-
7	-	-
8	-	-

Figure 16: Configuration for pole A capacitors (CA)

The transformer turn ratio is roughly the voltage multiplier for the raw voltage input. In other words, if the input is 100 mV and the turn ratio is 1:10, the resulting voltage will be in the order of 1 V. However, it is worth noting that the higher the turn ratio, the larger the resistance is at the input, yielding lower current going into the chip. The chip has a lower bound for input current, beyond which it will not operate. Furthermore, changing the turn ratio also implies changing the inductance of the coils in the transformer, which affects the oscillatory frequency.

Each pole has an input terminal, with two equivalent screw-down attachments. These are arranged so that they are grouped together on the upper left edge of the board as seen in Figure 9(a) and (b). Alternatively, they are on the leftmost tab of Pole A (Figure 13) and topmost tab of Pole B (Figure 14). A multipolar source is attached across Pole A's input terminal and Pole B's input terminal.

For a unipolar source, the source is attached across the input terminal of Pole A and ground, with the positive side of the source on Pole A's terminal. Ground is available throughout the board, but most convenient are the square pads on the upper right and lower right of the board. Pole B's input terminal should also be grounded when the board is used with a unipolar source.

Pole A and B have the same transformer turn ratios. Three switch blocks, TA1, TA2, and TA3, configure the turn ratio for Pole A, while TB1, TB2, and TB3 configure the turn ratio for Pole B. Figure 15 illustrates how the switches should be set to achieve the different ratio. For a given turn ratio, the figure shows which switch should be ON each switch block. The other switches should be off.

Switches	C1B [nF]	C2B [nF]
1	-	1
2	-	0.47
3	33	-
4	10	-
5	4.7	-
6	1	-

Figure 17: Configuration for pole B capacitors (CB)

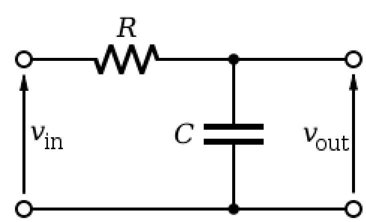
Each Pole has two capacitors that affect input behavior. For Pole A, these are C1A and C2A, while for Pole B, these are C1B and C2B. Figure 16 illustrates how to set switch block CA to select different values of C1A and C2A. The circuit is designed such that if multiple capacitors are enabled, their capacitance will add. For example, if CA-4 (10 nF) and CA-5 (4.7 nF) are both on, then C1A is set to 14.7nF. Switches 7 and 8 of CA should be left off.

Figure 17 illustrates how the capacitances for Pole B are selected. The active switches are identical to Pole A, although the switch block is smaller.

We often configure the output of the board (Section 4.6), attach the the intended load (recipient device) and power source (or close approximation), and then use an oscilloscope to see the resulting signal on C1 and C2. We then adjust the Pole blocks until we see a waveform that complies with chip expectation. Figure 18 shows the expected waveform at C2 when the board is correctly tuned.

ADVANCED

Pol A also offers a low-pass filter, the schematic of which is shown in the figure below. This allows the board to be part of a multi-stage power harvesting solution where higher than 100 kHz signals are harvested by a secondary board. This feature is out of the scope of this paper and will be left up to the advanced users to determine its use.



To enable the filter, turn ON *CA-7* (switch block CA, switch number 7). *CA-8* will connect the filter to ground, effectively grounding out any high frequencies. Alternatively, high frequencies can be picked up from the leg of *CA-8*. The ***cutoff frequency*** can be tunned using the pot labeled ***FAT***.

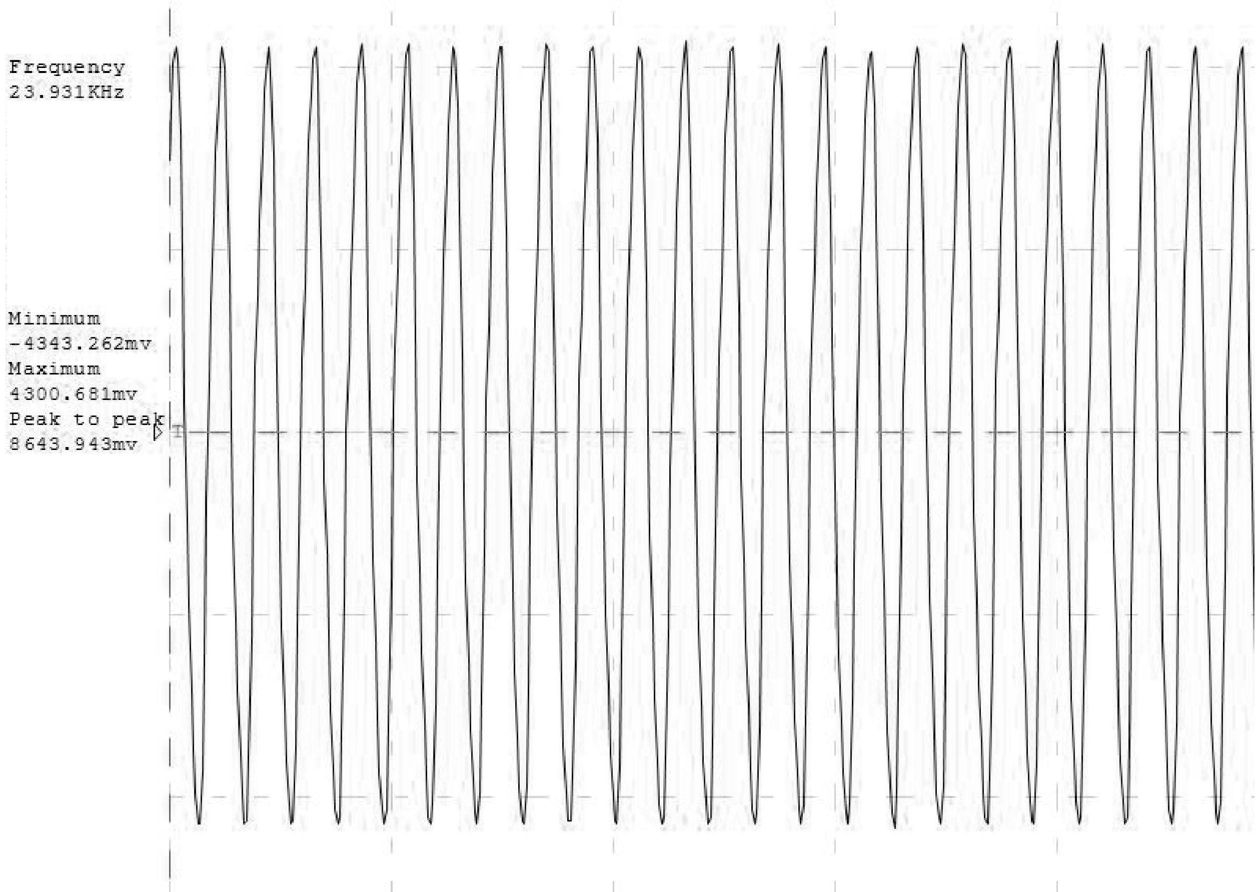


Figure 18: Expected waveform at C2 output when the circuit is correctly tuned.

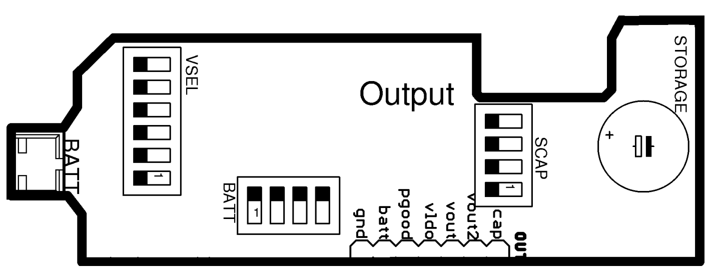


Figure 19: Output

4.6 Output configuration

The power harvesting module has three different outputs.

- Vout : Main output
- Vout2 : High power output
- Vldo : Low dropout output (LDO)

Switch	Output Voltage [V] 2.35	3.30	4.10	5.00
1	×	×	×	×
2	OFF	OFF	ON	ON
3	OFF	ON	OFF	ON
4	×	×	×	×
5	ON	ON	OFF	OFF
6	ON	OFF	ON	OFF

Figure 20: Configuring Output Voltage

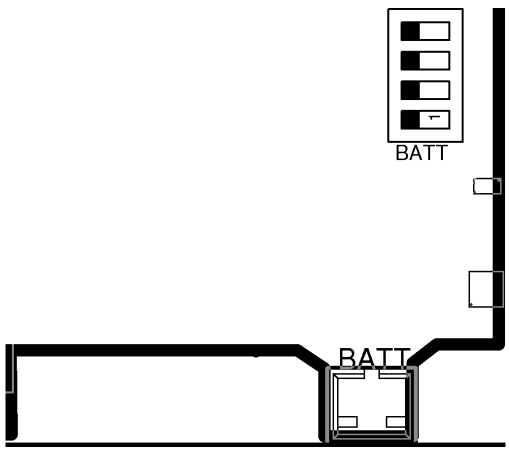


Figure 21: Battery backup

Vout and Vout2 are programmable such that one can choose the voltage to match the client device requirements. Figure 19 illustrates the output block of PowerMod.

The voltage is selectable using the switch block VSEL. Figure 20 shows the 4 possible output voltage targets and how to configure VSEL for them. The output block contains two additional switch blocks, BATT and SCAP, but these are related to energy storage in a battery or storage capacitor, which is distinct from the output voltage itself. We discuss these storage options next.

4.7 Storage configuration

There are two main choices for storage: batteries and capacitors. It is important to understand that any storage component has two inherent constraints. First, there is a lower, nonzero bound on the current needed to begin storing energy. Second, the stored energy will leak away. In order to accumulate energy, the current supplied by the output block of PowerMod must exceed both of these. Ultimately, this current depends on the source itself, the efficiency of conversion, and on how well PowerMod has been tuned to the input.

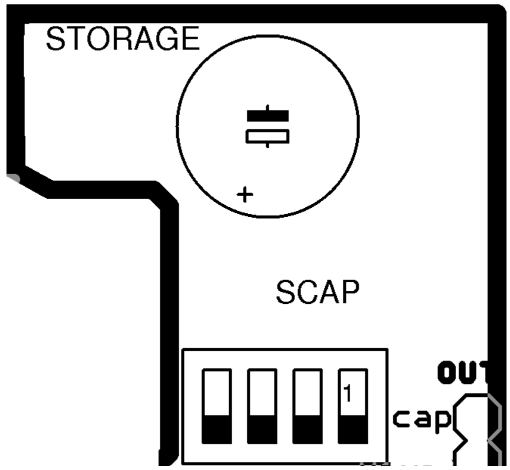


Figure 22: Capacitor storage

Switch	SCAP	BATT
1	Vout2	Vstore
2	Vout	Vout
3	VLDO	Vout2
4	Vstore	trigger

Figure 23: Configuring Storage Switches

PowerMod is able to charge a Lithium-ion battery, and there are solder pads for attaching one, as well as some physical room for a small one, as can be seeing in Figure 21. The battery can be configured to run the device when the source is not producing enough energy. For example, during night time in a solar powered solution. The battery could also be charged separately to provide a battery backup in the event of a power harvesting failure.

PowerMod is able to charge a capacitor or super-capacitor, and there is physical space, and solder pads on the board for a bank of varying size capacitors, as shown in Figure 22. There are some considerations to take into account when selecting a capacitor for a power harvesting solution, which we discuss in Section 4.8.

The SCAP and BATT switches are used to determine which output voltages are supplied to the capacitor bank and the battery, as shown in Figure 23.

Activating the trigger switch on BATT has the effect of turning on Vout2 only when enough energy has been stored such that the target voltage configured in the output block has been reached. Suppose that Vout is fed to a storage capacitor, the trigger is enabled, and the target device is attached to Vout2. The voltage across the storage capacitor will then rise as it is "filled up". Vout2 will not become active (and thus energize the device) until the storage capacitor is "full", and it will become inactive (and thus turn OFF the device) after a certain amount of energy stored in the capacitor has been consumed. It is important to note that there is hysteresis in this system: Vout2 will become active when the voltage is within 7.5% of the target, and inactive when the voltage drops below 9% of the target.

4.8 Storage capacitors

Capacitance determines how much energy a capacitor can store. The voltage rating of a capacitor determines the maximum voltage that can be safely applied to it. Another important property of capacitors that is the *equivalent series resistance* or *ESR*. Essentially, this is a measure of how difficult it is to fill the capacitor. Capacitors are available in many flavors with a wide range of ESRs, capacitances, and voltage ratings.

Plain English

Capacitors are storage components that store energy by accumulating electrical charge. One can think of a capacitor as a (charge) form of water bucket, with the capacitance being the volume of the bucket. Water can be poured into the bucket at a slow rate via a garden hose, and the accumulated water can be dumped out at a much higher rate. Unfortunately, a capacitor is a bucket that also has a leak. Over time, the energy stored in a capacitor will leak away. This is important because we want to fill the capacitor at a rate much higher than it leaks, otherwise it will take a long time to fill up, or will not fill at all. The ESR of a capacitor is analogous to the diameter of the garden hose used to fill the bucket. The smaller the opening is, the slower we can fill it.

The capacitance is generally chosen to support the desired duty period of the client device—that is, how long it should run once it is energized. One can estimate the necessary capacitance via Equation 4.

$$C_{out}\,[\mu\mathrm{F}] >> \frac{I_{Load[mA]} \cdot t_{pulse[ms]}}{\delta V_{out[V]}} \tag{4}$$

There are three points to keep in mind when working with charged capacitors. First, shorting the leads (touching them together) can be dangerous, specially for large capacitances (over 22 µF). When shorted, the current is virtually unconstrained and sparks can easily form. The second point is that capacitors are rated for specific maximum voltages. Exceeding the maximum voltage can have catastrophic results, destroying the capacitor, perhaps explosively. Finally, when very large capacitors (over 10 mF) are fully charged, they can deliver a painful shock. Handle storage capacitors carefully.

4.9 Deployment

PowerMod can be used in various ways. Thus far, we explained how to use it as a configurable

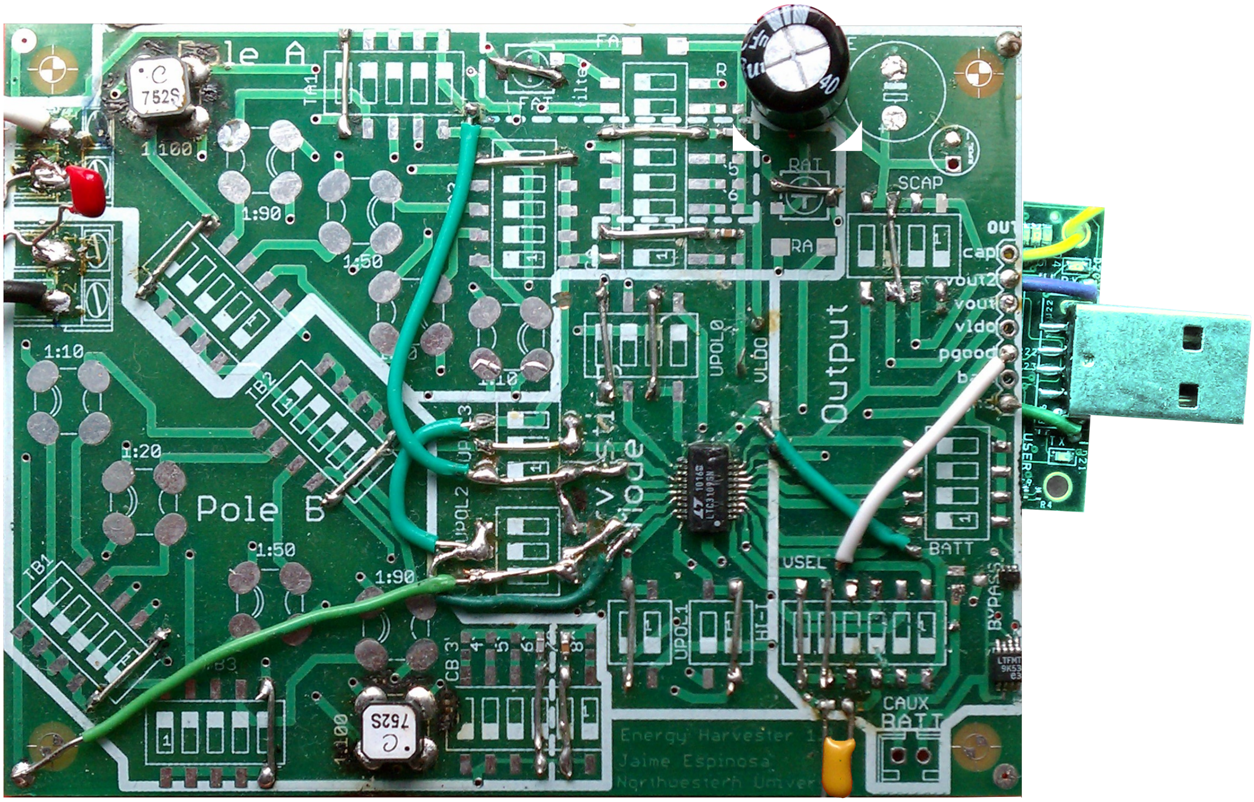


Figure 24: Example of a deployed PowerMod.

harvesting lab. Because it is small, it can be integrated into the end product like this, but to further cut costs for mass production, or to increase reliability by avoiding switches, components that are not used can be replaced or hard-wired. For example, one can use a wire instead of switches to make connections. An example of a board like this is shown in Figure 24. Notice that the switches were replaced with wires and the only components present are the capacitors and transformers that are specifically needed. This board has a Telos B mote attached to its back.

Notice that in this deployment example, the board is mostly "unpopulated" (many components are not mounted). It is possible to order the board like this, or assemble it by hand. The only components that are difficult to solder by hand are the chip and other surface mount components. There are YouTube videos that show techniques that make soldering surface mount (SMT) components much easier [8].

After a little practice we were able to work with the following tools to produce Figure 24:

- The most basic of soldering irons from Radio Shack.
- The soldering tip we use looks like a flat-head screw-driver (3mm).
- A wet sponge to clean the solder tip.

[8] Surface Mount Soldering Tutorial: `http://www.youtube.com/watch?v=3NN7UGWYmBY`.

- A spool of solder wick (with flux).
- Thin flux-core solder.
- A series of magnifiers and good lighting.
- Needle nose pliers.

5 Tutorial

In this section we give a step-by-step tutorial of how to use PowerMod. Note that the tutorial is not self-contained, but is intended to be be used in conjunction with the user guide of Section 4, which provides the details of configuring PowerMod, as well as more detailed explanations of the various terms used here. This tutorial also assumes that the reader has already chosen a environmental power source and its transducer.

5.1 Step 1: Characterizing the source

The first step is to characterize the output of the transducer when it is operating within the expected environment. To do so, an effective multimeter is needed. Multimeters come in various qualities and of course prices. The characteristics of the source that will be harvested will dictate what kind of multimeter will serve. Our general recommendation is the Wavetek 25XT. Any meter will work, but depending on the power source a resolution of at least 1 mA and 5 mV may be needed.

In addition to a multimeter, it is often quite helpful to also have an oscilloscope, such as a Link Instruments MSO-19.2, as we discussed previously. In addition to helping with the configuration of the board, an oscilloscope will also make it easier to determine whether there is a significant AC component to the source.

We assume that the transducer has two terminals across which is possible to measure. Some transducers may only have one obvious terminal because their other terminal is an earth or structural ground.

DC and AC: First, determine whether the source has a DC component—is its average voltage nonzero? To determine if there is a DC component, measure the voltage across the transducer using a multimeter configured in DC mode. If this is nonzero, it probably has a DC component. Second, determine whether it has an AC component—does its voltage vary across time? This is most easily done by connecting an oscilloscope across the transducer and observing the time-varying voltage directly on its screen.

Polarity: If the voltage measured across the source never crosses zero (i.e., is either always > 0 or always < 0, it is a unipolar source. Otherwise, it is a multipolar source. This measurement is most

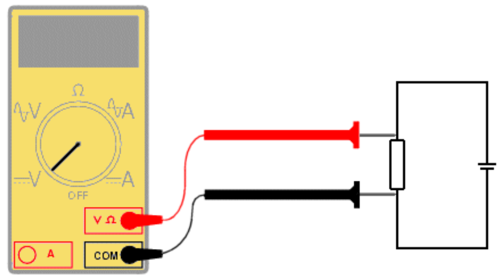


Figure 25: Measure Voltage

easily done with a scope. Note that it also a good idea to think through the polarity characteristics of the source over the long term. For example, the heat flux on a TEG might vary across seasons, the warm side changing from winter to summer, which would produce a corresponding polarity change.

Voltage: DC voltage can be measure by touching the multimeter probes to the transducer terminals. The multimeter must be set to DC voltage. Because PowerMod has an automatic polarity architecture, the order of the probes is not important. That is, it does not matter which terminal is chosen to be positive. Figure 25 shows how to connect the multimeter.

AC voltage can be measured with the multimeter in its AC position. Most multimeters are optimized to measure AC around 60 Hz, and other frequencies may incur error. It is preferable the use an oscilloscope instead. Adjust the oscilloscope amplitude and time division so that you see the maximum and minimum voltages. The difference is the peak-to-peak voltage. Also, by using a modern oscilloscope's frequency domain display, you can also identify the prevalent frequencies, if any. Some oscilloscopes may only display the single dominant frequency (i.e., frequency counter operation). Ancient oscilloscopes may require eyeballing the waveform.

Measuring current: DC current can also be measured using the multimeter. Strictly speaking current must be measured in series with the circuit. It is a measure of the flow of electrons, and the flow depends on the load attached across the transducer terminals. The input impedance of PowerMod is in the ballpark of 7 Ohms. To measure current, place a precision 7 Ohm resistor in series with the multimeter across the transducer terminals, as shown in Figure 26. It is important that that the multimeter be set to DC current mode, which usually also implies the use of a different plug, as shown in the figure.

To measure AC current, the load resistance is placed directly over the terminals of the transducer and the oscilloscope is used to measure the voltage across the load resistance. The waveform seen, divided by 7 ohms, is the AC current waveform. Note that we are assuming a purely resistive load in this analysis, but the PowerMod input is not purely resistive.

From this point on, we consider a thermoelectric generator (TEG) source which has the following characteristics when situated in its environment:

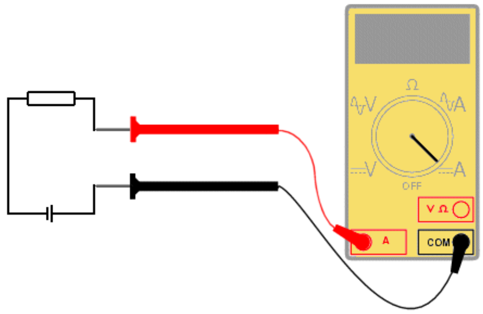


Figure 26: Measure Current

- DC and AC: It is a pure DC source.
- Polarity: It is a multipolar source since the voltage can reverse if the temperature gradient over it reverses.
- Voltage: 60 mV DC under typical conditions
- Current: 7 mA DC under typical conditions

5.2 Step 2: Configuring the board

Given the input characterization, you would next configure the DIP switches throughout the board, which are described in detail in Section 4. It is important to properly set the input switches or you can damage the board. In the following, we use the TEG characteristics given above.

Configure inputs: Given that the TEG source is multipolar, we must set the POL-A, POL-A.R, POL-B, and POL-B.C switch blocks according to Figure 11. In particular, we will turn ON POL-A-1, POL-A.R-2, POL-B-1, POL-B-2, POL-B.C-1, and POL-B.C-3, and leave the other switches on these blocks OFF.

We will set the high current protection OFF (Figure 12) as the TEG will not produce significant current under expected gradients.

We will configure both Pole A and Pole B identically. Because the TEG voltage is quite low, we will use a 1:100 turn ratio to maximize voltage gain. This configured using the TA[1,2,3] and TB[1,2,3] switch blocks as shown in Figure 15. Next we determine the capacitances (C1A, C2A, C1B, and C2B) experimentally, setting the switches as shown in Figures 16 and 17, starting with $C1A = C1B = 14.7\,\text{nF}$ and $C2A = C2B = 1.47\,\text{nF}$.

The resulting input configuration for each switch block is shown in Figure 27, where the ON are listed and all other switches are left OFF.

Switch Block	Switch Number
POL-A	1
POL-A.R	2
POL-B	1 2
POL-B.C	1 3
HI	1
TA1	1
TA2	5
TA3	5
TB1	1
TB2	5
TB3	5
CA	1 2 4 5
CB	1 2 4 5

Figure 27: Input Board Configuration for Telos B Thermal Harvesting

Switch Block	Switch Number
BATT	
SCAP	3
VSEL	4 5 6

Figure 28: Output Board Configuration for Telos B Thermal Harvesting

Configure Outputs: The output must be configured to match the device we intend to drive. PowerMod will provide a DC output of a specific programmable voltage and can source current until its stored energy is gone. The output current is limited differently depending on which output pin is used. For the sake of example, we consider powering a Telos B mote. Section 5.4 describes how PowerMod and the mote are connected. Specifically, we will attach the Telos B to the Vout2 output.

The Telos B requires 2.2–3.2 V (normally provided by two 1.5 V AA batteries) and requires 43 mA when computing and transmitting. ignoring its sensors and LEDs. We configure the VSEL switch block to a 2.35 V. The resulting configuration is shown in Figure 28.

5.3 Step 3: Connecting the capacitors

In our example we use the most common capacitors available. Refer to Section 4.8 for more details on capacitor choices available. We will use three parallel 1000 µF capacitors for a total of 3000 µF.

In principle, this amount of storage capacitance will allow the mote (at 2.35 V, 43 mA) to run for up to 400 ms once the capacitance is charged. Charging the capacitance from the 60 mV, 6 mA source will take about 14 seconds. The storage capacitance could be changed to change the both

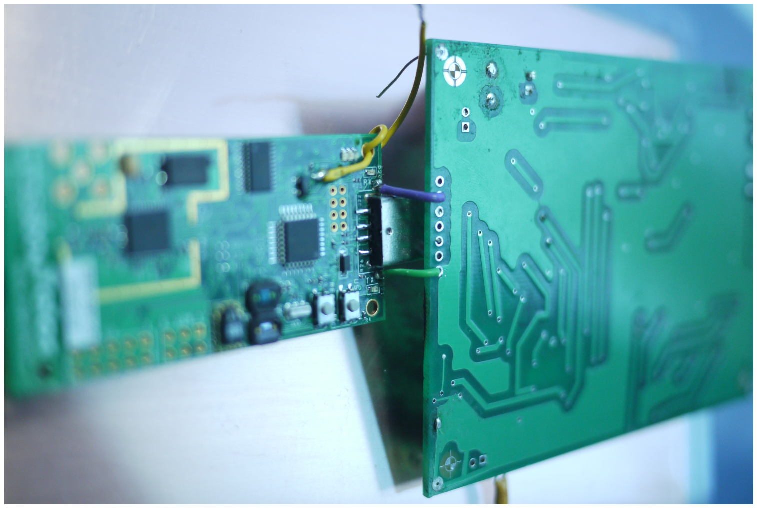


Figure 29: Telos B connected to PowerMod. Bottom view. Top view can be seen in Figure 24.

the length of the on period and the interval between on periods.

Because we are using capacitor storage, we will configure the BATT switch block to be entirely off, while the SCAP switch block will be set to use Vout2 (switch 1 on, others off), as shown in Figure 23.

5.4 Step 4: Connecting the mote

We programmed to Telos B mote for testing using the TinyOS *"Blink"* sample program, which can be found in `/opt/tinyos-2.1.1/apps/Blink`. TinyOS is the most common way to get started, but there are plenty of alternatives. The point is, it is helpful to start with a small program with known visual output (such as the LED) so that you can verify that PowerMod is working as expected. From there, more sophisticated programs can be used. Another useful debugging technique is to attach your oscilloscope to pin 1 of the 10 pin Telos B expansion connector, which the supply voltage (VCC).

The Telos B comes with a battery holder. In order to use PowerMod, cut the connections to the battery box as close to the box as possible so we can reuse the wires that are soldered in, then solder wires leading from these terminals to the Vout2 and ground pins on the right hand side of PowerMod. Figure 24 and 29 show a typical attachment from above and below.

Note that depending on the power needs of the target device the VLDO, Vout, and Vout2 outputs can all be connected together to increase the output current.

5.5 Step 5: Fine tuning

Once PowerMod is configured (Steps 1-4 above), its configuration can be fine tuned experimentally to further improve power conversion efficiency. To do so, we typically run the system with an oscilloscope attached to C2A, and then toggle switches until this voltage has been maximized. It is also possible to do this using a multimeter set on AC voltage and its reading multiplied by 1.4. 6 V peak is the maximum voltage your should see. If a combination of C1A and C2A (C1B, C2B) is found to exceed this maximum, decrease the turn ratio. Decreasing the turn ratio reduces the input resistance and improves efficiency.

Note that you should take into account higher input voltages that might occur in the environment, and leave headroom for them. For example, if using solar energy, tune the board for a sunny day. The board has *some* over voltage protection, but a sustained over-voltage or high voltage will damage the chip.

The efficiency and operation of the full system is a function of many factors. It is possible to calculate one optimum configuration, but tuning experimentally is the most pragmatic approach.

6 Design

The world is full of energy sources ready to be harvested. The method for extracting the energy may be very different from one source to the next. The electrical characteristics of the power provided from different transducers will vary considerably. Due to this complexity, power harvesting has been largely limited to researchers with an electrical engineering focus. For these reasons, we felt it would be helpful to the broader sensor networking community to design and implement an open source power harvesting system that was flexible enough to harvest from many sources, yet relatively straightforward to use.

Even though the world is full of energy sources, most of the sources are very low power, presenting low voltage or low current or both. It is then imperative that a power harvesting solution be as efficient as possible.

6.1 Goals

A power harvesting solution has four primary goals. First, it must be able to operate and usefully harvest energy from very low power inputs. This implies that its own power needs, its *quiescent current* times its operating voltage, must be low. Second, it must be able to provide the client device (possibly time-variant) voltage and current requirements. In other words, it should not be necessary to alter the client device in order to implement a power harvesting solution. Matching the requirements of the client device and the energy source is the key functionality that we focused on. The third goal is that the power harvester be usable by non-electrical engineers. Indeed, we would like PowerMod to be usable by typical sensor networking researchers. Our final goal is that the design be open and readily replicable so that such researchers can access it.

Available solutions for power harvesting are reviewed in Section 8. There are many good solutions, but we were unable to find a flexible open solution, suitable for non-experts, that allowed one to draw from a wide range of low power sources and deliver power to a range of clients, particularly sensor network nodes.

6.2 Theory of operation

The design of PowerMod is based on the Linear Technology LTC3109 power harvesting integrated circuit [17]. The peripheral circuitry is an highly configurable implementation of the different circuits outlined by the manufacturer. All the sample circuits available at the Linear Technology website and related data sheets can be implemented using PowerMod simply by setting switches accordingly. Additional circuits can be implemented by adding patches to the board.

The circuit design and board design pays special attention to minimizing unwanted resistance that would raise the minimum operating voltage. Much care was taken to minimize the loss of power due to the design or components utilized.

The LTC3109 is a surface mount integrated circuit that has a low loss rectifier, a power monitor and regulators in a single package. The block diagram for this IC (integrated circuit) is shown on page 8 of the datasheet [17].

The IC expects as input an AC signal in the range of 10 kHz to 100 kHz, a minimum current of 6 mA and maximum voltage of 6 V. As long as the input to the IC is within range, the module will scale the input voltage, store energy, monitor the stored energy, and regulate an output source.

To scale the small voltages often found in power harvesting applications, the input to the IC is a configurable flyback step-up converter circuit. The step-up converter induces an oscillation of a DC signal, and the ratio of windings of the transformer gives us the voltage multiplier. For example, in the ideal case a 1:100 transformer will step the voltage up from 10 mV to 1000 mV. However, transformers only work with alternating currents. The IC itself chops a DC input in order to allow the transformers to step up small DC voltages. The value of the capacitors help determine the oscillation frequency. Notice from the IC block diagram that the transistors are included. These are special power transistors that will work at very small signals.

This operation is replicated for both positive and negative polarity inputs, and thus also supports inputs that already have an AC component.

Given a properly formatted input signal, oscillating in the desired frequency range and with the desired peak-to-peak voltage, the IC rectifies the signal through a two-stage process to produce an internal DC bus voltage. This voltage is then used to derive selectable output voltages suitable for storage components such as capacitors and batteries. The range of configurability is determined by the specific components that are actually mounted. The voltage regulation functionality also provides signals that indicate the properties of the output voltages.

PowerMod includes an array of input transformers and capacitors that enables the user to dial in the most efficient configuration for their particular power harvesting source. The board also includes large pads to accommodate different transformers. However, we found that the Coilcraft miniature transformer series are very efficient and offer high enough winding ratio to allow operation from a 30 millivolt source. The board is designed to allow a selection of five transformers and six capacitors per pole. It also allows the configuration of several different output voltage levels, as well as interface configurability for storage capacitors and batteries. Space and pads for a range of these is included as well.

6.3 Schematic

Figure 30 is the schematic of the PowerMod design that is current at the time of this writing. The current schematic is included in the open source distribution file available from our web site. PowerMod was designed using Eagle CAD from CadSoft[9]. The free version of Eagle CAD is sufficient to read and modify this design.

[9] `http://www.cadsoftusa.com/`

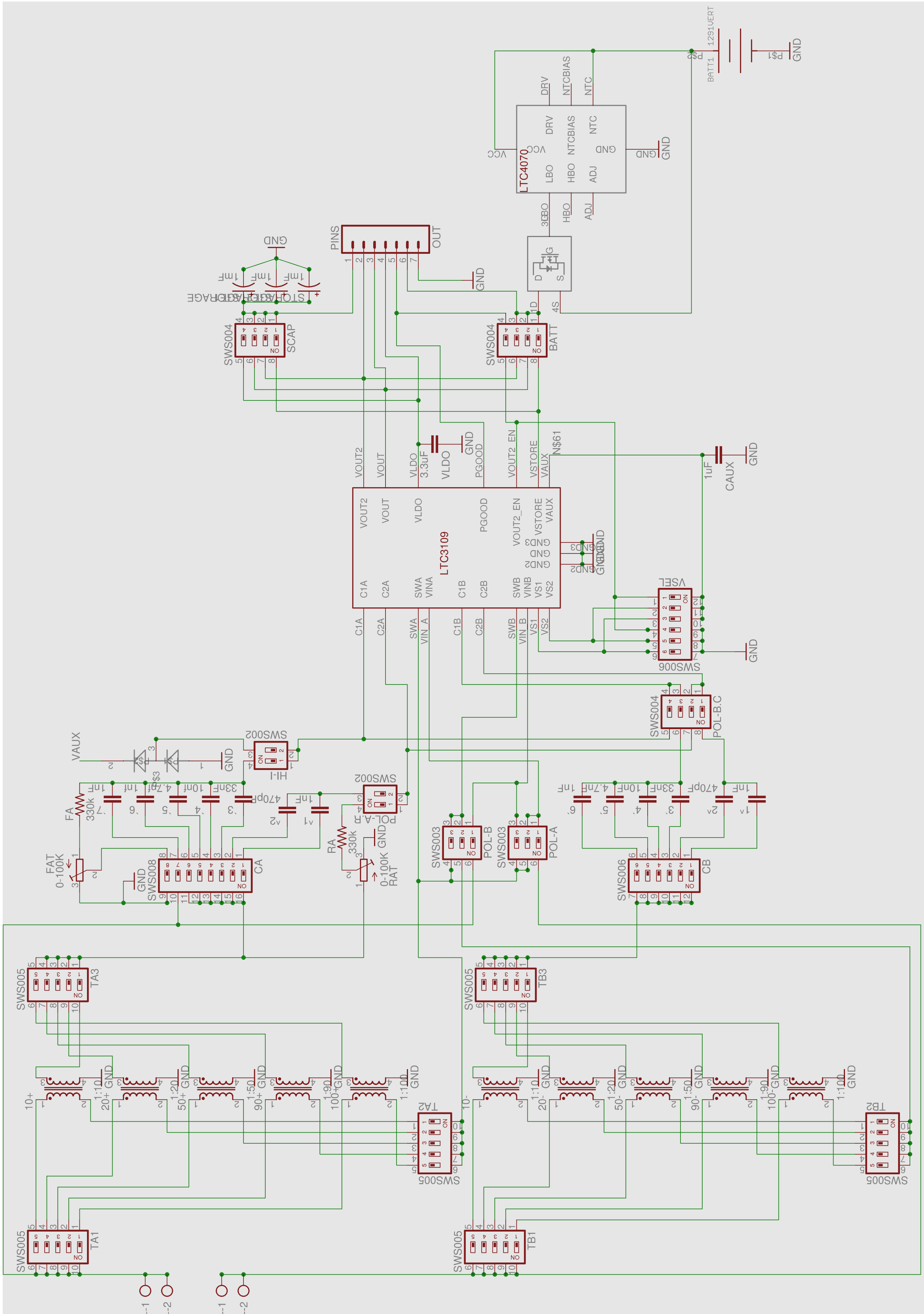


Figure 30: Schematic of PowerMod.

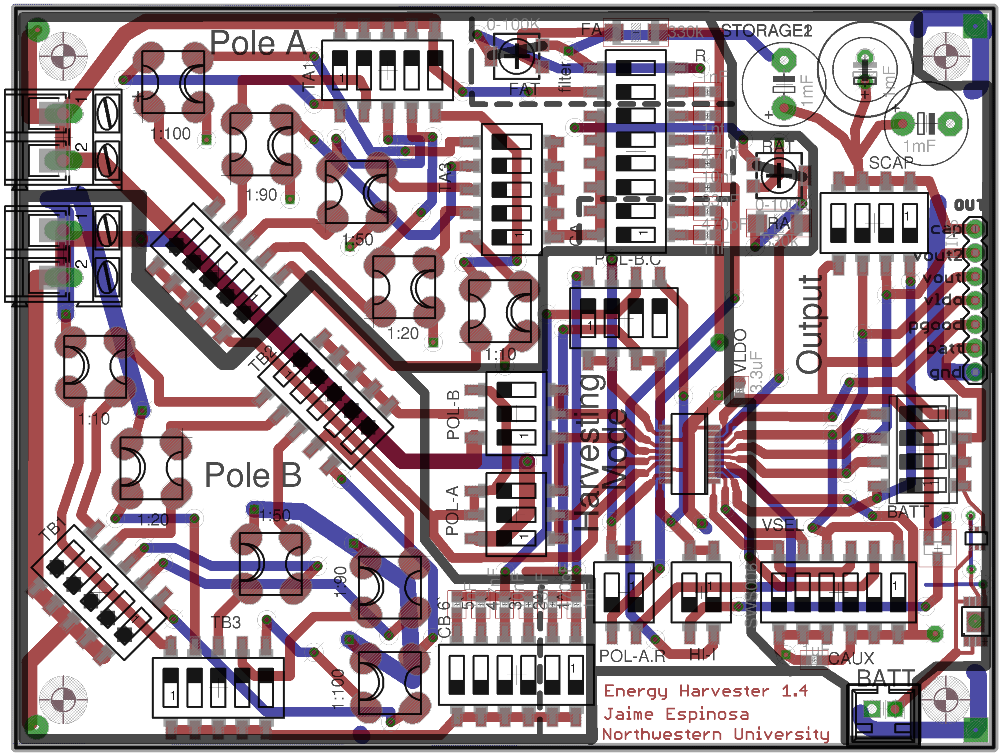


Figure 31: PCB layout of PowerMod. The ground plane is not shown.

6.4 Printed circuit board

Figure 31 shows the printed circuit board (PCB) layout that is current at the time of this writing. The current PCB layout is included in the open source distribution file available from our web site.

The PCB uses only two layers.Two layer PCBs are the cheapest multilayer PCBs and can even be built with off-the-shelf components. The design uses intentionally wide traces and wide spacing. Parasitic resistances, that is, unwanted resistances due to traces on the PCB, are inversely proportional to the width of the trace. Therefore, the wider the traces the less power is consumed by the PCB itself. Two-layer PCBs also make it possible to minimize parasitic capacitances because the spacing between traces can be controlled and made larger. Remember that capacitance is a function of the distance between conductors and the difference in their electric potentials.

Whenever possible component pads were designed larger than normal. Larger pads makes it easier to hand solder components to the board. Most noticeably, the pads for the transformers are extra large, which make it possible to hand solder the QFN component using a common solder iron and heat gun. The size of the transformer pad also allows an advanced user to experiment with transformers of different sizes.

6.5 Components

A detailed component list is included in the open source distribution file available from our web site. It is important to note that different input transformers and capacitors can be chosen to change the range of configurability the board has. In the following, we focus on the components that need to be carefully selected.

Switches: The specific switches, surface mount DIP switches, were selected because they introduce a low resistance. There are more convenient ways to switch the transformers, for example by using rotary switches, and there are better switches that help toggle signals. We had four reasons for choosing surface mount DIP switches:

DIP switches are inexpensive, compact

- Lower resistance. The resistance was nearly zero for our switches.
- Lower cost. DIP switches are less expensive than other independently packaged solutions. Also, since only a small number of classes of switches are used in the design, the switches can be bought in bulk more readily.
- Ease of deployment. Once parameters (set via switches) are optimized, it is straightforward to replace the switches with patches, lowering cost and making the deployed boards more rigid and reliable.

Input transformers and capacitors: In order to scale the input voltage from the millivolt range into something more usable, the LTC3109 and its external components implement a form of flyback converter. Figure 32 shows the circuit diagram for a typical flyback converter. There are three main components to a flyback converter: a transformer, a capacitor, and a transistor. The transformer and capacitors are on the board, while the transistor is part of the LTC3109 IC.

The transformer's main function to scale the voltage by the ratio of turns of its inductors. The inductance on the second winding of the transformer along the capacitance of C2 determine the

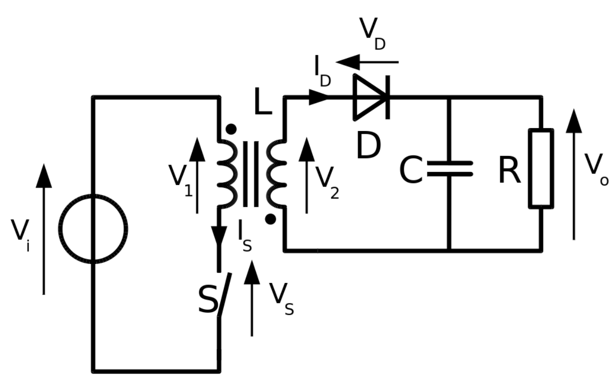


Figure 32: Flyback converter

oscillation frequency. This frequency is given by equation 5.

$$Frequency\,\text{Hz} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{secondary\_winding} \cdot C2}} \tag{5}$$

The main characteristics of transformers include, inductance for all coils, resistance for all coils, and turn ratio.

7 Evaluation

We tested PowerMod with various power sources to harvest from, including a TEG, a solar cell, and corrosion (Section 2). There are a great deal of choices in the market, and new materials are becoming available monthly.

It is helpful to characterize the performance of PowerMod independent of particular sources and transducers, to form a profile of its operation with respect to inputs. From an electrical perspective, we can characterize a source as being either voltage-limited or current-limited. We will ignore second order effects such as internal capacitance, resistance or, inductance. These details are rarely available and can be overcome experimentally using the procedure illustrated in our user manual.

To study PowerMod in this way we created an experimental setup that used a desktop power source that can be set to limit either voltage or current. The Agilent E3631A power supply gives us very fine resolution in setting current and voltage limits programmatically. The power supply feeds the input to a PowerMod , which in turn feeds an LED and small resistor at its output. These draw about 50 mA, similar to a mote. An Agilent 34970A Data Acquisition Unit is used to programmatically measure and record voltages and currents at critical points on the PowerMod during operation. an oscilloscope is attached to the output load LED and is triggered by the PGOOD output of PowerMod so that we can capture the duty cycle of the LED.

This setup is scripted so that we can sweep through different combinations of input voltage and current limits, and see the effects on the output, in particular whether PowerMod activates (harvests at all), how efficiently it does so, and what the duty cycle on the load is. Note that the parameter space that must be swept contains not only the different input voltage and current constraints, but also the PowerMod configuration itself, as well as the load characteristics. The actual parameter space is gigantic and cannot be fully explored. Thus, we focused on particular corners of the the space.

Figure 33 shows an example result, considering different configurations of the board. Each of the 12 graphs is an IV curve for the input of the PowerMod . In all cases, the input is voltage is limited, and the current draw is measured. The data is predominantly for unipolar operation, but the IV behavior is similar for the multipolar case. For Pole A, different combinations of turn ratio, CA1, and CA2, the primary configuration options, are considered.

The upshot of our test results is that PowerMod operates nearly optimally, by which we mean that our results reflect the best case performance described in the LTC3109 datasheet. In other

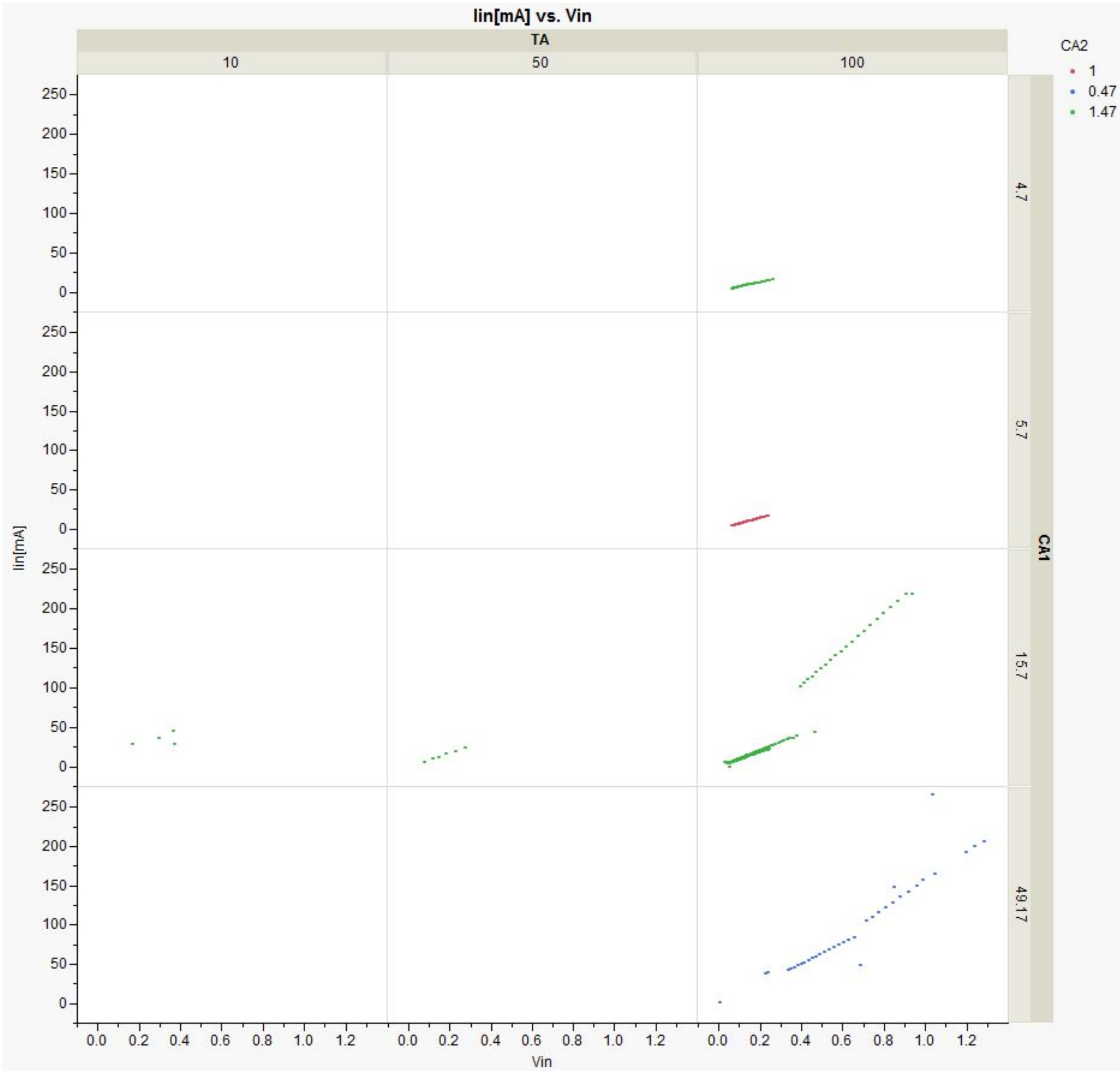


Figure 33: Input current / input voltage characterization as a function of turns ratio (TA) and capacitor values (CA1, CA2).

words, the flexible board design itself does not affect the IC's basic performance characteristics. Based on the tests, we determined that the board design and the components introduces negligible parasitics. That is to say, the resistance, the capacitance and the inductance introduced by the PCB layout and components is negligible. However, our results do show some unexplained temperature dependencies.

8 Related Work

PowerMod has two key goals. First, it is designed to support harvesting of extremely low voltage/current sources. Second, it is designed to facilitate use by the non-experts.

There is considerable work on energy harvesting. The market for sensor networks and energy harvesting has grown and commercial products are increasingly available.

Low power components are available that facilitate embedded system design and make harvesting a viable power source. Examples of such components include the following. Microchip XLP [19] microcontrollers specialize in low power and can be found in a variety of configurations. In sleep mode they consume as little as 9 nA, and some can run on 30 µA. Nordic Semiconductor offers a ultra-low power system on chip (SOC) [21] that integrates a microcontroller and transceiver in a single IC. The EcoMote [22], the smallest WSN mote we know of, is based on this IC[10]. The Texas Instruments MSP430 [29] has for a long time been the standard in low power microcontrollers. There is a great community built around this product line and hence a lot of support. The Telos B [23] is based on this microcontroller. The Analog Devices ADuCRF101 [3] is a system on chip that integrates a microcontroller and an ISM-band transceiver in a single package.

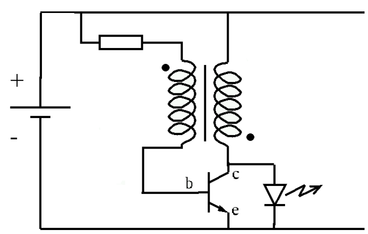
There are many types of wireless sensor network solutions and many more applicable microcontrollers, transceivers, and SOC components. We emphasize extremely low power components at the expense of features or computational might.

Power harvesting is an active area of research and there exist many offerings. The following components or works are particularly relevant. The Analog Linear Devices Inc.EH300 [1], is a power harvesting solution that can operate at 4 V and 200 nA. We evaluated this chip, but were unable to implement a circuit that was sufficient to drive our Telos B test platform. DURACAP [9] is a power harvesting system that uses solar energy and stages of supercapacitors to intelligently monitor and manage power (using a dedicated microcontroller). EnOcean [11] is a company dedicated to power harvesting. They offer modules for power harvesting, sensors, switches, controllers, and repeaters. The power harvesting modules are specifically built for motion, heat, or solar energy. The HelioMote [16] can power most common sensor network motes using solar energy harvesting. The Joule-Thief is an easy to construct circuit that uses a few common, *discrete* components and has become rather popular. It operates on voltages from 0.75 V. More details are offered later. The Linear Technologies LTC3109 [17] was chosen to be at the heart of PowerMod because it can operate at 0.3 V] and 6 mA, can be configured for a wide operating range, and provides output choices. The Maxim MAX17710 [18] is a charger and protector for rechargeable batteries that can start charging from a 0.75 V and 675 [nA] source with up to 95% efficiency. Powercast [24] specializes in harvesting from radio-frequency (electromagnetic) sources. Powercast produces an IC that connects to an antenna, captures radio waves and provides a power source to a client device [12]. The IC is tunned to respond best to a frequency around 900 Mhz. To complement the availability of 900 Mhz radio waves, the company also produces a strong emitter that pumps radio waves into the environment, transmitting power to remote nodes. The ST Microelectronics SPV1040 [28], is a single chip step-up converter that can harvest from 0.3 V and 60 μA.

[10] `http://www.ecomote.net`

Advanced

The *Joule Thief* is a simple circuit similar to a flyback converter, that is generally built using extremely inexpensive discrete components [14]. It uses the switching capability of a transistor, the thresholds of a diode and the magnetic charging quality of an inductor to produce an oscillation. This oscillatory signal is then amplified by the coupling with another inductor. The diode is typically an LED, which then lights up at every pulse. The oscillations are fast enough to be imperceivable. The Joule Thief is generally used to extract further energy out of a depleted battery to power a light. It could potentially be used to extend the running time of battery-powered sensor nodes. The Internet is filled with sample uses for the Joule Thief as well as variations on the circuit. Examples can be found at `http://rustybolt.info/wordpress/?p=12`.



What a Joule Thief cannot do is operate with very low voltage and current sources. It generally needs input voltages that exceed 0.75 volts. The relatively low efficiency of the circuit may also become an issue. We note that zero threshold transistors [2] might be a way to get around some limitation, but design and results are still under development.

While numerous individual components exist, there are no systems that meet the goals we set for PowerMod . A general purpose configurable power harvesting system that is easy to use is not readily available. Power harvesting surveys present comparisons of energy sources [8],[30], and [26]; but do not take into account the losses and minimum limits that energy can actually be harvested and put to use. Specialized power harvesting solutions are optimized for a specific operating condition and do not offer flexibility to tune the circuits to the actual deployment environment without sacrificing efficiency.

9 Conclusions and future work

We described the design, implementation, and evaluation of PowerMod, an open-source hardware platform to enable flexible and configurable power conversion in power harvesting. PowerMod has been designed to support both low voltage/current regimes of operation, and to be usable by non-experts. Our hope is that our design will make possible for the general sensor network community to adopt power harvesting in their designs without major efforts. PowerMod was designed to be as flexible as possible, both to adapt to a wide range of sources, and to act as a lab for power harvesting. We described the range of operation of the board in this document. The design files needed to fabricate an instance of PowerMod are available from our web site.

We are continuing to consider various extensions of this work. One goal of this work is to reduce the minimum operating voltage and current of the PowerMod. One approach is to add an input stage that operates at lower voltages. We think that this can be done using zero threshold transistors and a modified boost converter. Another approach is to widen the frequency response by adding a high-pass filter that would divert frequencies of over 100 kHz to a secondary harvesting board. A third approach would be to enhance charging of storage components, for example using the Seiko Z228 component. The Seiko itself might also be usable instead of the LTC3109, resulting in a simpler platform.

The second goal of the future work is to further simplify the use of the PowerMod, or components like it. This would require considerable enhancements to the configuration algorithms, and an embedding of these algorithms into software. Additionally, a programming model that supports power harvesting-driven operation in a first class way is clearly needed. It is important to understand that typical operation with power harvesting is *sporadic* simply because the operating power of the node exceeds the available power in the environment. How to enable non-experts to program to such sporadic operation is a major challenge.

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