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Energy scavenging system for indoor wireless sensor network

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ABSTRACT

ENERGY SCAVENGING SYSTEM FOR INDOOR WIRELESS SENSOR NETWORK

by
David Andrew Crea

As wireless communication evolves wireless sensors have begun to be integrated into society more and more. As these sensors are used to a greater extent newer and better ways to keep them working optimally have begun to surface. One such method aims to further the sensors energy independence on humans. This technique is known as energy scavenging. The logic behind energy scavenging is to allow the device to have its own reliable source of energy that does not require upkeep, has a long life expectancy, and does not completely rely on an internal power source. The aim of this thesis is to research techniques for indoor energy scavenging for sensor that is used to monitor patients in a hospital.

There are numerous techniques to achieve energy scavenging in wireless sensor networks. Multiple scavenging methods are known such as vibration energy, thermoelectric energy, and photovoltaic energy. All of these methods were analyzed and compared to see which would be optimal for the situation the sensor would be put in. Other techniques come into play to help the efficiency of the sensor network. These methods were also examined to help the energy scavenging to be more feasible.

ENERGY SCAVENGING SYSTEM FOR INDOOR WIRLESS SENSOR NETWORK

by
David Andrew Crea

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ENERGY SCAVENGING SYSTEM FOR INDOOR WIRELESS SENSOR NETWORK

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Dedicated to my loving parents Roger and Stephanie Crea, who gave me the strength, support, and motivation needed to see my work through to its completion.

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CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this thesis is to analyze and develop a theory for an indoor wireless sensor network for monitoring patients in a hospital that utilizes energy scavenging in order to stay operational and can stay active all day long.

In order to achieve this goal a few topics need to be taken into consideration. First of which is form of energy scavenging that will be used. There are multiple types that are applicable. The system can use vibration energy, thermoelectric energy or solar energy. All three will be analyzed to see which is the most efficient in the given situation.

Also aside from the analysis of the types of energy scavenging the set up of the internal circuit for the individual sensors must also be analyzed such that they can properly relay the energy obtained from an outside source. The design of a sensor network must also be taken into account so that the sensors can maximize the power they consume.

1.2 Background Information

Although energy scavenging seems like a newer concept it is in essence no different from the use of windmills and waterwheels. The only thing that is new is the use of the idea in the engineering world. Many researchers see the potential of a purely autonomous device that does not need to rely on anything but itself in order to stay active. Many movements are being made to find uses for these techniques in everyday society. Not only are wireless sensors one of the major aims of energy scavenging but also mobile devices such as a wrist watch powered by the kinetic energy generated by arm movement. Also many unmanned aerial vehicles utilize solar energy scavenging to stay aloft. Energy scavenging is a technology that is expanding not just because it is practical but also because it is environmentally friendly.

Sensors are also a technology that has been around for quite some time. A thermometer is a type of sensor as well as the part of a garage door opener that receives the signal from your car. The idea of a wireless sensor is a sensor that can communicate and transfer its information without needing a direct connection to what it is transferring its data to. However a few other points come into play when dealing with wireless sensors, such as methods for detecting other sensors, data processing methods, and data transfer rates. There is a careful balance that must be maintained within a wireless sensor network in order to keep it operating at the maximum efficiency.

The aim of incorporating energy scavenging into wireless sensors is so that we can have a device that can accumulate, analyze and relay information without needing a user to monitor the device to make sure it remains active, in essence a device that can take care of itself. This would allow us to only worry about the initial placement of a sensor and not have to worry about constantly checking to make sure that the device is still working properly. We would simply know that the device is still operational.

CHAPTER 2

ENERGY SCAVENGING TYPES

There are three main types of energy scavenging that are used in sensor networks. As mentioned before they are vibration energy, thermoelectric energy, and solar energy. Each one of these types of energy scavenging has its own situation in which it is useful. Also aside from simply relying on a constant stream of power from the energy scavenging system, it is also possible to have a rechargeable battery existing inside the system that the excess power will overflow into for situations where the primary energy scavenging source does not suffice.

2.1 Vibration Energy

Vibration energy utilizes a form of kinetic motion to generate energy for a system. There are three types of vibrational energy sources [Priya and Inman, 2009]:

- Piezoelectric materials: Systems in which mechanical strains across a material layer generate a surface charge, and when an oscillating load is placed on the structure an AC power source results.
- Inductive systems: Systems in which a magnet moving through a wound coil induces a current through the coil, akin to an electric motor.
- Capacitive systems: Systems in which a charge on a capacitor is “pumped” by varying the distance between the plates of the capacitor. In this case, the harvester always requires a voltage source from which to pump.

The equation for calculating the power generated from a vibrational energy source is as follows [Priya and Inman, 2009]:

$$P = \frac{m\zeta_e A^2}{4\omega(\zeta_e + \zeta_m)^2} \tag{2.1}$$

Where A is the acceleration of a proof mass m, ω represents the frequency that the system is vibrating. ζ_e stands for the electrical dampening coefficient and ζ_m is the mechanical damping coefficient. From the equation alone it can be deduced that power increases with an additional acceleration and mass on the system, but decreases when frequency and dampening coefficients increase.

In the end the amount of energy that is harvested is limited by moving sources and most system designs are affected greatly by driving frequencies. When dependent on the driving frequency, the systems can only provide their peak power in a narrow power band. Table 2.1 shows the achievable power for each vibrational system design:

Table 2.1 Comparison of Various Vibrational-Harvesting Technologies for use with Wireless Sensor Networks

Technology	**Power**	**Condition**	**Size**
PZT	0.375 mW	9.1 g, 2.25 m/s^2,85 Hz	1 cm^3
Electromagnetic	3 mW	50 g, 0.5 m/s^{2,} 50 Hz	41.3 cm^3
Capacitive	3.7 µW	1.2 mg, 10 m/s^2, 800 Hz	0.75 cm^3

Source: [Priya and Inman, 2009]

By analyzing this table and the information we have so far we can come to a few conclusions. First of all, capacitive systems do not generate nearly as much power as the other two. However, they are more reliable. They also rely on a voltage source to pump from. Consequently for our purely wireless system this is no applicable. Electromagnetic, or inductive, systems look quite efficient, but when you consider how much more space they take up and that they use magnets on a coil, it may not be as usable as it seems. It requires 40 times the space of piezoelectric sources and when the power produces is looked at in a mW/cm^3 stand point electromagnetic only produces .073 mW/cm^3. However, a piezoelectric generator produces .375 mW/cm^3. We can see that piezoelectric is a better system than the other two.

A deeper look into piezoelectric systems is required to get a complete grasp on the subject. The following figure shows what a typical vibrational energy system looks like:

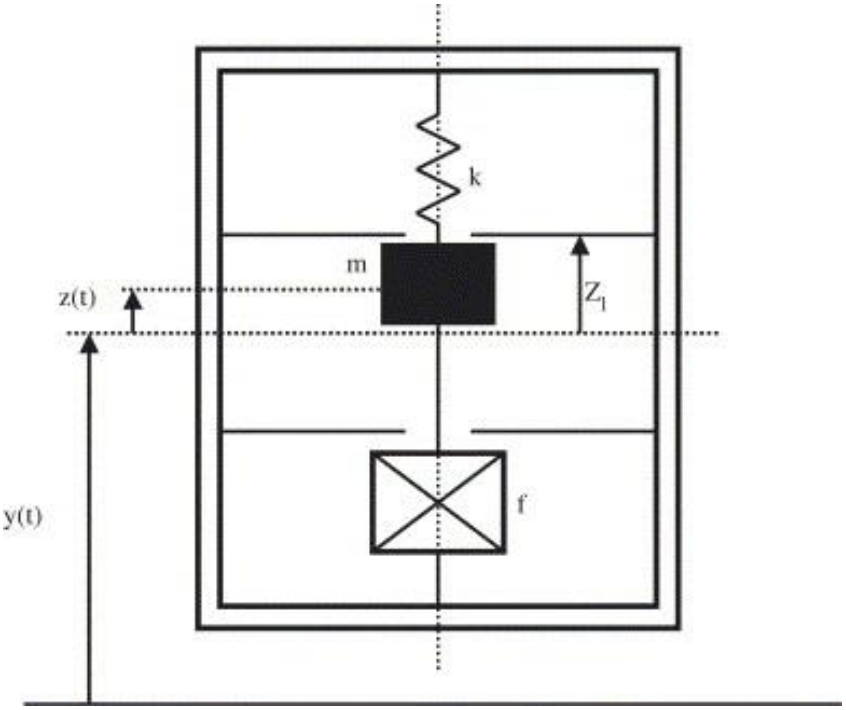

Figure 2.1 Schematic of a generic vibration-driven energy scavenger.
Source: [Cantatore and Ouwerkerk, 2006]

In order to expand upon Figure 2.1 we will estimate the power generated by a vibration energy scavenging system. First consider that the sinusoidal input vibration of amplitude Y_o applied to the frame of the generator, such that $y(t)= Y_o \cos(\omega t)$. $y(t)$

represents the input oscillation. It causes a relative displacement of $z(t)$ between the proof mass and the frame. This causes the mass m to create work against the damping force f, either caused by a magnetic or electric field or by a straining a piezoelectric material, mattering on whether it is an inductive or piezoelectric system. This work is converted into electrical energy.

With a mechanical system that is linear, the motion of the proof mass, $z(t)$, is a result of the sinusoidal frame displacement, $y(t)$, will be in synchronization with the same frequency of excitation, $z(t)=Z_o \cos(\omega t + \theta)$. As a result the maximum displacement of the proof mass within the frame is equal to $Z_l = \max[Z_o]$ which is restricted to the available generator volume or the maximum allowed spring deflection. As a result of the output power increasing with Z_o, $Z_o = Z_l$ when in an optimal vibration-driven generator.

With electromagnetic generators, the damping force is fairly proportional to the velocity of the mass with respect to the frame such that $f = Dz(t)$ and system shown in Figure 2.1 is linear. In these devices the maximum possible electrical power Pmax, which is only generated when the frequency of the input oscillation is the same as the mechanic resonance frequency of the system ω_n and $Z_o = Z_l$, is [Cantatore and Ouwerkerk, 2006]

$$P_{max} = \frac{1}{2} m Y_o^2 \omega^3 \frac{Z_l}{Y_o} \tag{2.2}$$

This equation is also valid for piezoelectric generators by taking into account their hysteretic damping where the retarding force is proportional to the velocity and inversely proportional to the frequency of the vibration.

With equation (2.2) we can estimate the maximum power generated by the vibration-driven generator with a given volume, which determines *m* and Z_l, and is subject to a given excitation source amplitude *Yo* and frequency ω. This concept is applied to the following three situations: [Cantatore and Ouwerkerk, 2006]

- the knee of a man walking at 4 km/h on a treadmill
- the case of a microwave oven in operation
- the tread of a tire on a car traveling at 100 km/h

We assume that the generator is about 100 mm^3 so the maximum value for m is 1g. For a generator that has standard precision engineering techniques the optimistic Z_l = 10 mm. When this data is applied to equation (2.2) we get the following table:

Table 2.2 Maximum Output Power Achievable by Vibration Driven Generators in Different Kind of Practical Applications

Vibration Source	F(Hz)	A_o (m/s^2)	Y_o (m)	m (kg)	Z_l (m)	P_{max} (W)	Z
Man Walking	6	1.96	$1.4x10^{-3}$	10^{-3}	10^{-2}	$3.7x10^{-4}$	$7x10^{-2}$
Microwave Case	120	2	$3.5x10^{-6}$	10^{-3}	10^{-2}	$7.5x10^{-3}$	$1.8x10^{-4}$
Tire Tread	100	100	$2.5x10^{-4}$	10^{-3}	10^{-2}	$3.1x10^{-1}$	$1.3x10^{-2}$

Source: [Cantatore and Ouwerkerk, 2006]

From this table we can see that a normal man walking can produce about .37 mW as stated earlier as well. But now it is shown that it is possible for a man walking to produce this much. Considering that standard microsensors consume about 100 μW of power, this source of energy would be sufficient. However it is stated that the sensor is on the knee of the man so we would have to do further tests to see how much energy would be produced from sensors placed on different parts of the body for proper medical testing. Furthermore this is also taken into account that the subject is constantly moving, if not the power produced would lessen over time as the dampening slows down the acceleration of the proof mass. Therefore, other tactics of energy scavenging must be taken into account, but this source will not be so quickly written off, simply put aside until later.

2.2 Thermoelectric Energy

In environments that naturally produce temperature gradients and heat flows can be used to produce energy through the use of thermal-to-electrical energy conversion. However the amount of power that can be produced is limited by Carnot and material efficiencies, as well as heat availability. The amount of power produced by a thermoelectric energy scavenger may not be enough to run most machines. Remote wireless sensors on the other hand have low power requirements and are perfect for thermoelectric energy scavenging.

A thermoelectric generator is a solid-state device with no moving parts. The way that a thermoelectric generator produces energy is through the charge carriers in the metals and semiconductors that make up the generators. These charge carriers can move freely as if they were gas molecules while carrying charges. When the temperature gradient is applied to the material inside of the generator the charge carriers at the hot end moves towards the cold end. This movement causes a buildup of charged carriers and results with a net charge at the cold end. This net charge produces an electrostatic potential. Equilibrium is then reached between the chemical potential for diffusion and the electrostatic repulsion due to the buildup of charge. This is known as the Seebeck effect[Priya and Inman, 2009].

The temperature difference across the generator provides a voltage $V=\alpha \Delta T$ where α is the Seebeck coefficient. The heat flow drives the electrical current, and thus it determines the power output. The thermoelectric figure of merit of the materials zT depends on the Seebeck coefficient α, absolute temperature T, electrical resistivity ρ, and thermal conductivity κ of the material such that: [Priya and Inman, 2009]

$$zT = \frac{\alpha^2 T}{\rho \kappa} \tag{2.3}$$

The maximum efficiency of the device is largely determined by its figure of merit ZT which is mostly an average of the different components zT values.

For power we follow a similarly simple equation. First we must determine the Carnot factor, which limits the work of heat [Priya and Inman, 2009]:

$$\eta_{Carnot} = \frac{\Delta T}{T_h} \tag{2.4}$$

Where $\Delta T = T_h - T_c$, T_h is the hot temperature, and T_c is the cold temperature. Also we have ΔT_{TE} which is the temperature difference across the device and η_r which is the reduced efficiency, relative to the Carnot efficiency. This gives us the efficiency η such that [Priya and Inman, 2009]:

$$\eta = \Delta T_{TE} \frac{\eta_r}{T_h} \quad (2.5)$$

From this equation and also using the generators heat Q we can determine electrical power P through [Priya and Inman, 2009]:

$$P = \eta Q \quad (2.6)$$

Using these equations we can determine that the amount of energy that can be produced by a normal person's body heat, which is where our sensor would be located, is about 22 μW of power [Priya and Inman, 2009] However, as mentioned before, the standard sensor uses up about 100 μW of power. Hence, the use of a thermal sensor is not a viable solution. However, developments into the field of thermoelectric generators may improve the power output in the future. Also, thermoelectric power is a much more reliable source because body heat is a constant output, it could also double as a temperature sensor, but for now we will consider other power sources.

2.3 Photovoltaic Energy

Photovoltaic energy scavenging is the use of solar cells to convert light into energy. This can include artificial lighting as well as natural light. It is also the best producer of power when running at max efficiency of all the energy scavenging type, reaching up to 100 mW/cm^2 during mid-day with no cloud cover. This kind of generator has been used for years now to power small devices such as pocket calculators.

A photovoltaic cell can be made of different materials, all of which have a different turn out rate for energy conversion. The following figure shows the differences between different materials placed under a halogen lamp with 160 W of electrical power. This lamp was moved closer to get a different range of illumination ranging from 10^4 to 150 lux [Priya and Inman, 2009], a lux is a unit of illumination measurement where one lux is defined as the illumination provided by a full moon on a clear sky over the tropical latitudes:

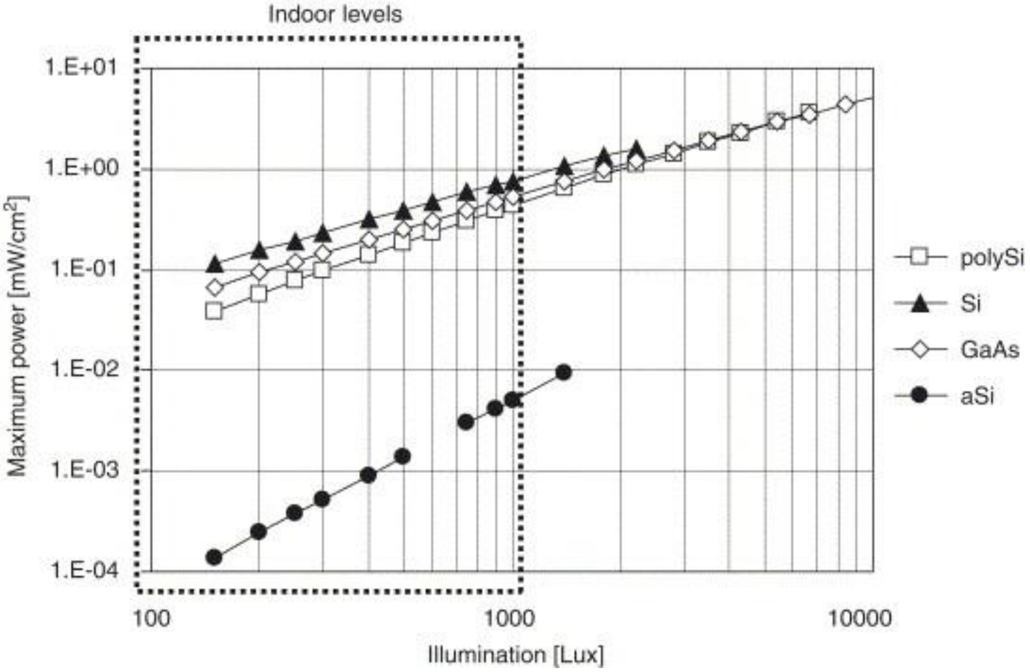

Figure 2.2 Maximum power generated by photovoltaic generators under indoor illumination conditions.
Source: [Priya and Inman, 2009]

From this we can assume that Silicon cells would work the best in these situations. Now normal office/hospital lighting is typically between 320 to 500 lux which would generate somewhere from .3 mW/cm^2 to about .5 mW/cm^2. This would be more than enough to power any wireless sensor.

It is apparent that solar cells can potentially produce the most power out of all the possible energy scavenging types. The data given are only with one cell on a device. Photovoltaic cells are quite small and it would be easy to simply place two or more on a device to further produce more energy than one could. You would simply have to place the cells in series or place a DC-DC converter in the system to boost the potential by diminishing current. However the problem still lies in that photovoltaic sensors lose effectiveness as the day moves on. However some methods can be taken to circumvent this. One such method is to include a battery in the circuit that will power up from excess power and be used during down times to keep the circuit running. These methods will be discussed in more detail later on.

2.4 Summary

We have gone over three different types of energy scavenging, photovoltaic, vibrational, and thermoelectric. When we look at thermoelectric we come to the conclusion that it is not worth using. Vibrational energy scavenging seems like a viable option. However, the energy produced from this type implies that the patient is constantly moving, which most hospital patients usually are not. The final choice is photovoltaic, which seems very possible, except at night the sensor is not able to get much power and would either shut down or would have to rely on a different source.

The conclusion that we have come to is to utilize three different techniques in order to produce a working sensor. First, we use a number of photovoltaic cells whose quantity needs to be determined via testing. Second, we will use a Piezoelectric vibrational energy generator. Lastly, a rechargeable battery that can store excess energy will be installed on the device as well. This set up is to cover all of the possible complications that may arise. The photovoltaic cells would be the main power source. They would be able to absorb light and convert it even when the patient is immobile in their bed. The Piezoelectric vibrational energy generator is for the situations that the patient might be in from time to time where not enough light is able to reach the photovoltaic cells. The battery is for the nights when the patient is both stationary and there is a lack of light, at these times the battery will take over. The battery can also be used for times when both the photovoltaic cells and the Piezoelectric generator cannot provide enough energy. With these three systems in place we are confident that the sensor will always receive enough power.

CHAPTER 3

CIRCUIT DESIGN

3.1 Energy Scavenging Implementation

As stated in the last chapter, there are two ways to integrate energy scavenging into the circuit design of a wireless sensor. The first is you can implement the energy scavenging generator on the circuit by itself with no other support. The second is to install a battery or ultra capacitor onto the device as well such that it is charged from the overflow charge that the device does not use. This stored charge can be used during downtime where the generator cannot power the device, because energy scavenging can be fickle.

3.1.1 Circuit Without Internal Battery

When a device does not have an internal rechargeable battery it must solely rely on the energy scavenging method implemented on it to power it completely. In some cases multiple types of energy scavenging may need to be used to power the device to cover for the downtime of one of the power methods. But aside from that the circuit must also be implemented in such a way that the energy can be properly relayed to the device. If we use more than one type of energy scavenging we must take this into account and either implement them in series so that the power can accumulate properly, or a relay to control the voltage and power that reaches the device.

This method of energy harvesting is usually not used however. Very few wireless sensors that use energy harvesting operate without an internal battery source. It has been stated that energy scavenging is fickle in its reliability. Although all the different kinds of energy scavenging techniques are good sources of energy, all the ones presented have a chance of failing. A sensor with a vibrational generator can have its movement stop, a sensor with photovoltaic energy scavenging is less effective at night than during the day, and a sensor with a thermoelectric generation loses its energy creating capabilities if the temperature lowers. Utilizing more than one type of energy scavenging can help to lower this percentage of failure. However all it does is lower it, it does not remove it. The inclusion of a battery though can greatly reduce the chance of failure by filling in for the generators when they cannot provide the required power. The next section will look into a layout using a battery with more detail.

3.1.2 Circuit With Internal Battery

For most wireless sensors designs, the one including an internal rechargeable battery is a good idea. It allows the sensor to have a backup power supply. This allows the sensor with vibration energy and photoelectric energy to function properly when there is no sunlight and no movement. The battery is charged during times of excess energy flow and used during times of energy shortage.

We now need to design the hardware using the given parameters. A simple block diagram of the overall design is given in Figure 3.1:

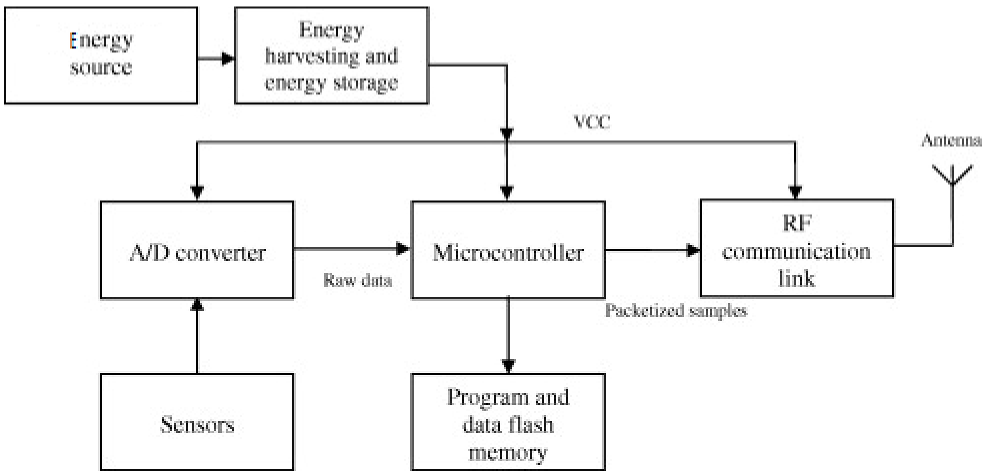

Figure 3.1 Block diagram of an energy harvesting wireless router node.
Source: [Hande, Polk, Walker, and Bhatia, 2007]

The flow of data through the machine can be as follows; the sensor records the data from the patient and relays the analog signal to the A/D converter. The converter then transforms the analog signal into digital data which is then sent to the microcontroller which forwards any data to the flash memory and relays the rest of the information to the Radio Frequency communication link. Next let us take a closer look at the energy harvesting part of the design as shown in Figure 3.2:

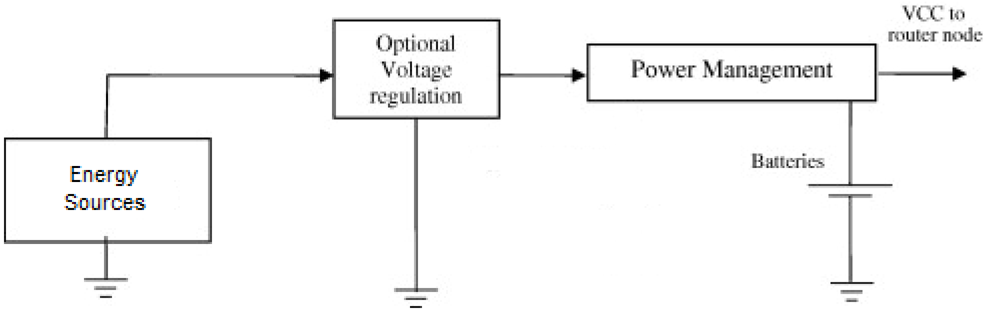

Figure 3.2 Block diagram of an energy harvesting system.
Source: [Hande, Polk, Walker, and Bhatia, 2007]

The energy scavenging sources send the generated power through a power management unit. If required an optional voltage regulation unit is installed in order to better regulate the movement of energy from the two different generators. Once the voltage reaches the power management unit, the voltage is distributed in such a way that the excess voltage runoff that is not needed to power the sensor components are forwarded to the batteries. This voltage is used to charge the batteries so that they can be used when the energy scavenging generators cannot produce the required amount of energy to power the sensor. This design shows pretty well the general idea of how the sensor works. Another point that needs to be covered in order to fully understand the device is the energy consumption algorithm.

3.2 Algorithm for Energy Consumption

There is of course an algorithm for the rate at which power is consumed by the sensor. In this section we look at the general version of the power consumption algorithm in terms of time. A majority of this is theory and has to be adjusted if the actual device is ever made. Experimentation has to be done to compare actual results to the theory in this section.

First we need to look at algorithm for energy production, or source. We consider a function $E(t)$ which is continuous, bounded, and a function of a continuously varying parameter t that represents time. $E(t)$ is known as a $(\rho, \sigma_1, \sigma_2)$ source if, and only if, for any finite real number T, it satisfies: [Bulusu and Jha, 2005]

$$\int_T E(t)dt \geq \rho T - \sigma_1 \tag{3.1}$$

$$\int_T E(t)dt \leq \rho T + \sigma_2 \tag{3.2}$$

This equation only has three parameters which keep it analytically tractable but still allows it to model a wide variety of variations in energy sources. Again *E(t)* is a function of power output in terms of a time variable *t*. The algorithm shows the asymptotic rate of availability, and the maximum power at which the system can operate. The restrictions on *E(t)* are justified because it is a physical system. It is to be noted that the ρ is in power or watts and σ_1 and σ_2 are in energy or joules.

Furthermore as well as a source algorithm we also need a consumer algorithm such that the device is said to be a (ρ', σ) consumer if the power consumption of the device *E(t)* satisfies:

$$\int_T E(t)dt \leq \rho' T + \sigma \tag{3.3}$$

By utilizing these two algorithms we can determine how long a system can stay active. If we have a (ρ', σ) consumer device that is powered by a $(\rho, \sigma_1, \sigma_2)$ source, which also contains and energy storage threshold of $\sigma+\sigma_1+\sigma_2$, and if $\rho' < \rho$, then our device can operate for an infinite period of time. The main idea of this algorithm is that it allows us to characterize the energy availability of a system by using only a small number of parameters. The idea of power management can be used to further allow for leniency in the algorithm. In the next section we will discuss different power management techniques to lower the energy consumption of the system.

CHAPTER 4

SENSOR NETWORK OPTIMIZATION

4.1 Energy Cost in Relation to Data Transfer

When considering data transfer in a sensor network you have to consider the cost of transferring each piece of data. Each piece of data uses a portion of power to transfer. One way to consume less power is to use cross-layer optimization techniques that make the system more energy-efficient. By analyzing each layer we can determine different ways to lower power consumption by trading some other trait.

Starting with the hardware layer we see that the most important technique for this layer is low power circuit design. The aim is to create dedicated low-power, low-cost hardware modules for the expected performance levels of sensor nodes. We also want to look at the tradeoffs between power consumption of the system and other performance metrics. For a sensor node we want a performance criterion that is around the tens of MIPS. This would allow us to design simple digital circuits with less power consumption.

Regarding simple circuit design we also can look into two types of tradeoff. The first is energy vs. response time. In this tradeoff type we need to select the appropriate shutdown mode in terms of the tradeoff between shutdown duration and wake-up time/energy cost. We can determine the shutdown duration by looking at the tradeoffs between energy efficiency and possible miss rate at the application level. However, this is not really a viable option because the sensors that we are designing need to be on constantly with no time for sleep

Another more viable technique is voltage scaling, or energy vs. delay trade off. In this method we reduce the speed of the CPU such that there is a longer duration per instruction while we use less power per instruction. This is a better option than the previous one because it only delays the sending of data, usually by a negligible amount. Furthermore since this technique uses the idea that the power consumption is quadratically proportional to the supply voltage, this allows us to lower the voltage input to the system and send more of the run off to the rechargeable battery.

Next we look at the physical layer; optimization here is achieved by power control, rate adaptation, and adaptive coding. These techniques have many cross-layer effects and make it difficult to isolate the tradeoffs. Because of this, such an impact eventually affects the network connectivity, topology, data transmission rate, and energy costs at various layers. However we can come to the conclusion that power control explores the tradeoff of energy vs. connectivity while rate adaptation and adaptive coding have the tradeoff between energy and communication speed or transmission delay.

Power control is originally made for single-hop, multi-user systems, such as cellular systems, to maintain a given level of signal-to-noise quality to compensate for fading effects, thermal noise, and mutual interference in the shared radio spectrum. In wireless sensors power control is used for determining an appropriate communication radius. Power control schemes can also be used to reduce the communication radius, and thus power consumption. Rate adaptation and adaptive coding are also first developed for cellular systems and local wireless networks in order to produce throughput optimization. The techniques for scheduling packet transmission over a given channel with delay constraints is converted to use in wireless communication which will be discussed in more detail later on.

Next we analyze the MAC layer, which affects energy efficiency through transmission scheduling and channel access. The common way to do this is by sleep scheduling. One such method is by PAMAS (Power Aware Multi-Access with Signaling) protocol, which is a protocol that turns off nodes that cannot transmit due to traffic. Another type of protocols is S-MAC nodes, which determine their sleep scheduling based on the sleep schedule of the surrounding nodes. Also there exist T-MAC nodes that are similar to S-MAC ones but can adapt their scheduling process on the fly. However the tradeoff in sleep scheduling is energy vs. delay as well as buffering size. Also there is another tradeoff of energy vs. topology, which affects concurrent transmission scheduling and channel access at the MAC layer [Yu, Prasanna and Krishnamachair, 2006].

The routing layer uses many protocols that are developed for address-centric networks. One such protocol is known as direct diffusion information processing, which is seen as an opportunistic by-product of routing. This protocol is not good for applications with complex information processing due to the lack of formal consideration for integration information processing with routing. The LEACH protocol is an empirical study that aims for energy conversion by avoiding long distance communication, not integration of information processing with routing. Lastly, entropy-aware routing is the use of data aggregation on k pieces of information and a Shallow Light Tree (SLT) routing scheme.

Lastly in the application layer the general idea is to trade application level information precision or accuracy for energy. With prediction-based data gathering of a one dimensional random Gaussian field, if the group size within the predicted field is increased then computation cost increases as well but communication cost decreases. This introduces the idea of tunable compression, which allows for balanced computation energy cost vs. communication energy cost scenarios. This will be analyzed in more detail later on.

The idea to take away from this is that optimization techniques are not independent in a wireless sensor network system. A single performance metric can be affected by techniques across multiple layers. The idea is to find a factor of your system that you can afford to sacrifice in order to lower the energy cost for the whole system. If the system needs to be on only once a day then sleep scheduling is a good option. If not then you must analyze other aspects of the system.

4.2 Energy Saving Methods

This section discusses a few of the more viable options for the system. This includes data compression, voltage scaling, data rate, and network topography. Each of these techniques differs from one another in a number of ways and allow for different options for saving energy.

4.2.1 Data Compression

With data compression we have to make a comparison between the energy cost to compress a unit of data and the energy cost to transport data. This technique is known as tunable compression. It is difficult to define a general form for characterizing the energy costs of various compression schemes. Instead we use a simple model that captures the principles behind tunable compression, and show how the computation time complexity of compressing one unit of data is inversely proportional to the output size. We define γ, which abstracts the relative energy cost of compression one unit of data normalized by the cost of communicating one unit of data. Also defined are s which is the size of the data packet and f that is the output size after compression. The following is the function of the energy cost $g(f)$ [Yu, Prasanna and Krishnamachair, 2006]:

$$g(f) = s\gamma\left(\frac{s}{f}\right) \tag{4.1}$$

From equation (4.1) we can conclude that s indicates that the energy cost is proportional to input size. The term s/f signifies that the energy cost is also inversely proportional to the compression ratio.

Next we look at the tradeoff between computation and communication energy, γ still represents the relative energy cost of compressing one unit of data normalized by the cost of communicating one unit of data. f still denotes the output size and ω_e denotes the cost of transmitting a unit data packet over a link between two nodes. The resulting equation for $\epsilon(f)$, which represents overall energy costs, is [Yu, Prasanna and Krishnamachair, 2006]:

$$\epsilon(f) = \left(\frac{\gamma}{f}\right) + f\omega_e \tag{4.2}$$

The plot of $\epsilon(f)$ is a convex parabolic graph. Hence, in order to find the point where the least amount of energy is used we merely need to find where $\epsilon'(f) = 0$. At that point of compression is the best balance of energy consumed by data compression and data transmission.

4.2.2 Voltage Scaling

Three major components of power consumption for executing the computation task by a CMOS integrated circuit: switching power, short-circuit power, and leakage power. The focus of this section is on switching power, which dominates the power consumption in most cases. V_{dd} denotes the supply voltage, f_{clock} denote the clock frequency, C_L denotes the loading capacitance, and P_t denotes the probability that a power-consuming transition occurs (the activity factor). The switching power P_{sw} can be modeled as [Yu, Prasanna and Krishnamachair, 2006]:

$$P_{sw} = P_t * C_L * V_{dd}^2 * f_{clock} \tag{4.3}$$

Power consumption increases quadratically with supply voltage. Basically, power consumption can be reduced by decreasing the supply voltage. However, by decreasing the supply voltage we also reduce the processing speed, and therefore increased processing time τ, which can be shown by [Yu, Prasanna and Krishnamachair, 2006]:

$$P_{sw} = k_c \frac{V_{dd}}{(V_{dd} - V_T)^2} \tag{4.4}$$

In this algorithm k_c is a constant and V_T is the threshold voltage. In the end, ϵ which is the energy cost can be found by the product of P_{sw} and τ. It will increases linearly with V_{dd}. As energy cost decreases, the execution delay increases. Hence, in application the device needs be monitored to see what is the longest the data can take to get to its location so that the maximum voltage reduction can be done.

4.2.3 Data Rate

The rate at which data is transferred can also affect the amount of energy consumed by a system. The faster data is transferred, the more power needed to energize the device. If we have a communication task that transmits a packet of *s* bits between two sensor nodes, with the symbol rate R_s, that is fixed and a modulation level of the sender in terms of the constellation size *b*, then we can calculate the transmission time τ [Yu, Prasanna and Krishnamachair, 2006]:

$$\tau = \frac{s}{b * R_s} \tag{4.5}$$

The corresponding transmission energy can be modeled as the sum of output energy and electronics energy, which can also be determined by *b*. To show off the tradeoff between energy and latency, we look at the equation $\omega(\tau)$ such that: [Yu, Prasanna and Krishnamachair, 2006]

$$\omega(\tau) = \left[C_{tr} * \left(2^{\frac{s}{\tau * R_s}} - 1\right) + C_{ele}\right] * \tau * R_s \tag{4.6}$$

Also C_{tr} is determined by the quality of transmission and the noise power, and C_{ele} is a device-dependent parameter that determines the power consumption of the electronic circuitry of the sender. Two more equations are needed to see the results, i.e. one for output power P_o and another for electronic power P_e: [Yu, Prasanna and Krishnamachair, 2006]

$$P_o = C_{tr} * R_s * (2^b - 1) \tag{4.7}$$

$$P_e = C_{tr} * R_s \tag{4.8}$$

By plotting we can see that the graph is hyperbolic such that as b decreases so does the energy consumed. However so does the transmission time. Thus we have to find the optimum number of bits per second to transmit. The only way that the optimal transmission rate changes is how long of a distance the device is transmitting. Longer distance communications can transmit just as well at higher rates as it can at lower rates. When it comes to shorter transmission ranges the energy cost actually increases at higher rates. For our system which is a short range communication range, we would prefer somewhere in between high and low transmission rates.

4.2.4 Network Topology

On final aspect is the actual design of the sensor network. What this means is that the placement of the nodes is just as important as the routing algorithms. For instance if there are routing nodes along the path between the source nodes and the sink nodes then the transmission range of the source node can be limited so as to use less power. However we must experiment with the placement of the nodes to make sure that the routing nodes along the path are always next to each other from the source to the destination.

One idea for node placement for the sensor network is to place a number of wireless nodes in a grid formation around the hospital. These nodes would be wired to power sources so energy scavenging for them would not be necessary. Then the wireless sensor node on the bodies of the patients would have their transmission ranges restricted such that the communication range can be remarkably small. This allows for smaller power consumption from the nodes as they transmit to the many router nodes around the building. This also makes sure that the source nodes never walk outside of their transmission ranges while moving around the building. This method of energy conservation requires a great deal of experimentation and testing in order to see if it turns out any positive benefits.

CHAPTER 5

ENERGY CONSUMPTION ANALYSIS

5.1 Sensing and Transmission Components

Actual calculation and experimentation are required to show that a device can be operational for a period of time. By examining existing sensor components we can determine whether the theorized device is plausible or not. If we look at the amount of energy it takes to perform certain operations we can predict how much energy the device consumes per second, also by predicting how much energy is produced we can establish a theorized lifespan for the device in different situations. The final device design is a system of sensors on the body that record different vitals and relays these vital signs to a routing node placed on the center part of the body that routes the data to the main server. Also by analyzing the energy consumption of a transmitting device, the conclusion can be reached that the chargeable battery must be charged prior to being placed onto the device.

For these calculations three resources are used. First is the CC1100E series transmission device. This is a low cost device only consuming about 30 mW a second at full use [Texas Instruments 1]. The second device is a small temperature sensor, the TMP112 series, not an actual medical sensor. Note that we fail to find the specs for the latter. From this temperature sensor the power consumption for a medical temperature sensor is derived [Texas Instruments 2]. The final component is the battery to be used in the device. A battery that would be used on a body sensor needs to be small but powerful at the same time. For this a button battery the CR2405 battery is a desirable choice. It can produce up to 1.86 Watts per hour if needed [Energizer]. By taking these three devices we can create three different prediction algorithms for energy consumption for two different devices and two different energy production algorithms from the generators that we decide to use.

5.2 Calculation of Energy Consumption for a Sensor

Energy consumption on the temperature sensor can be calculated in this fashion. The Amps and Volts needed for the temperature sensor are 85μA and 2V [Texas Instruments 2]. Also the cost to transmit is 1.8 V and 15 mA [Texas Instruments 1]. To overcome this extreme cost we shall have the device only transmit the temperature if there is a .5 degree change in the temperature since the last time the temperature was transmitted. This however will cost power to do a comparison each time the temperature is taken, predicted to cost about 100 μW each time. Furthermore it is known that a photovoltaic generator can produce 500 μW a second under indoor lighting [Priya and Inman, 2009] and a piezoelectric generator can produce 370 μW per second for a man in motion [Cantatore and Ouwerkerk, 2006]. It is also assumed that because the data to be transmitted is so much smaller than the kBand of a transmission device we can assume that all the data is transmitted in less than one second. From these values known we can calculate the cost per second and the energy produced. We can assume that the piezoelectric generator is only active when the body is at work, so at rest the generators produce 500 μW per second and when at work the generators produce 870 μW.

The power consumption for each device is determined by if the body is at work or rest. For the temperature sensor the equation for power consumption while the body is at rest is:

$$2V * 85\mu A * t + 100\mu Wt + 1.8V * 15mA * \frac{t}{5} \tag{5.1}$$

The 2V*85µA represents the work done by the sensor, the 100µW is the work done to compare the values, and the 1.8V*15mA is the work done by the transmission device. The t/5 is there to show a predicted time frame for how often the transmission device will have to transmit, i.e., one every 5 seconds. From this equation combined with the data that at rest only the photovoltaic generator is active generating 500µW of power and that the battery has stored 1.86 Watts per hour of energy or 6696 Watts per second, then we obtain the results shown in Figure 5.1:

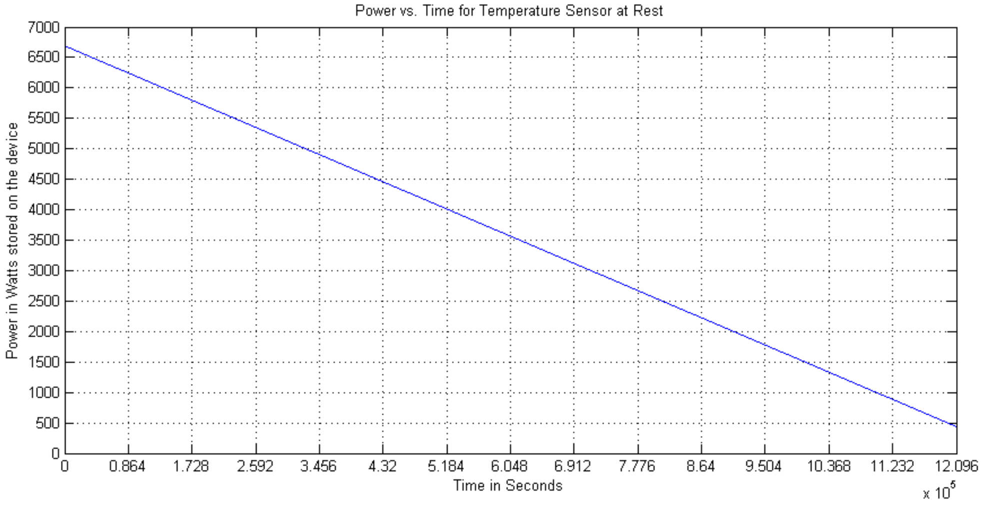

Figure 5.1 Power vs. time for temperature sensor at rest.

Each point on the X axis in this chart is a day, from this we can see that the temperature sensor can run for two weeks at rest with no problem. Now when the body is at work we can expect the temperature of the body to change more often, so for the at work equation can be found by changing the frequency that we transmit data to once every two seconds:

$$2V * 85\mu A * t + 100\mu W t + 1.8V * 15mA * \frac{t}{2} \tag{5.2}$$

This combined with the fact that at work the piezoelectric generator is also active at work resulting in 870µW per second being generated, we have the results as shown in Figure 5.2:

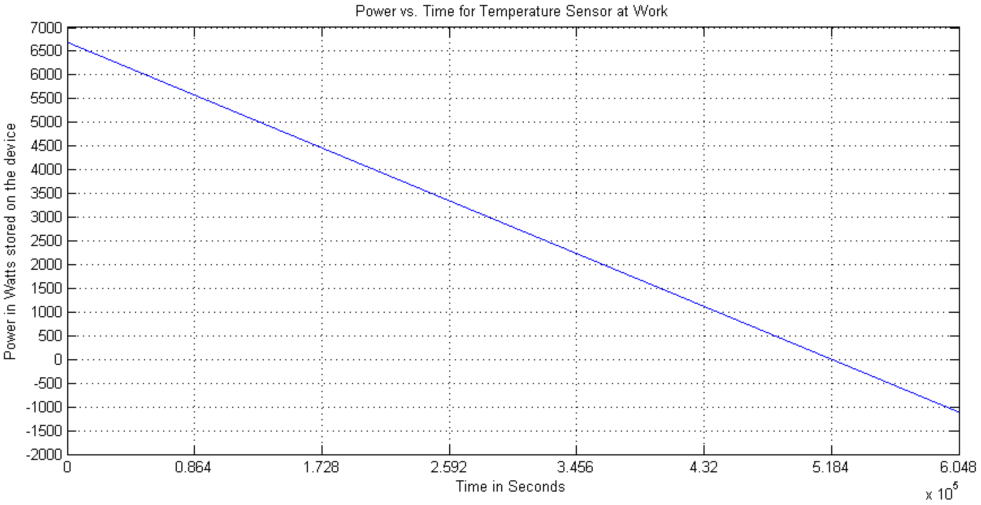

Figure 5.2 Power vs. time for temperature sensor at work.

The sensor at work cannot last for as long as it can at rest for sure but it still lasts for a good five days time. Furthermore this is under the idea that a person would be active for five days straight. The idea for a body at work is for a patient who needs rehabilitative work. However there will be no situation with a body is constantly at work and constantly at rest for such long periods of time, so instead we will simulate a week with a common schedule for a patient in a hospital receiving rehabilitation. Rehabilitation is different for each patient [World Confederation for Physical Therapy] so we shall be using an assumed rehabilitation schedule. The daily schedule for our theorized patient is; 3 hours of rehabilitation, 9 hours of sleep, and 12 hours of being awake and resting. The resulting values are that the sensor will transmit once every 2 seconds while at work, once every 5 seconds while at rest, and once every 10 seconds while the patient is sleeping. If we properly graph these times over the course of a week, so the patient sleeps from midnight to 9am, rests from 9am to 3pm, has rehabilitation from 3pm to 6pm, then rests again from 6pm to midnight the result is Figure 5.3:

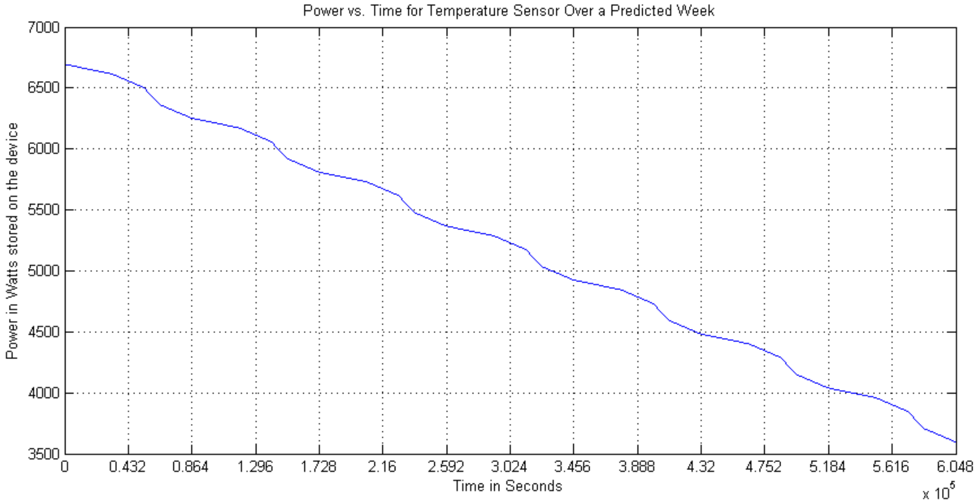

Figure 5.3 Power vs. time for temperature sensor over a predicted week.

Each vertical line in this graph represents 12 hours. We can see how during a normal scheduled week the device uses a little under half its power. Therefore, the device can in fact run for more than two weeks in a theorized situation.

5.3 Calculation of Energy Consumption for a Routing Node

Now that we know that the temperature sensor works fine we must now analyze the routing node that is be placed on the center of the sensor network on the patients body. This routing node does not transmit directly to the data server rather it transmits to other routing nodes placed around the hospital that act as hops to relay the data to the server. The equation for energy consumption by the routing node is as such:

$$(1.8V * 200nA) * \frac{4t}{5} + (1.8V * 16mA + 1.8V * 15mA + 1.8V * 1\mu A) * \frac{t}{5} \tag{5.3}$$

The 1.8V*200nA is the power consumed while in sleep mode while the other values are the power consumed when receiving and transmitted respectively and the last set of values, 1.8V*1µA is the wake up time. Furthermore because this is at rest it is assumed that data would not be changing very often and four fifths of the time it will be in sleep mode. The results are given in Figure 5.4:

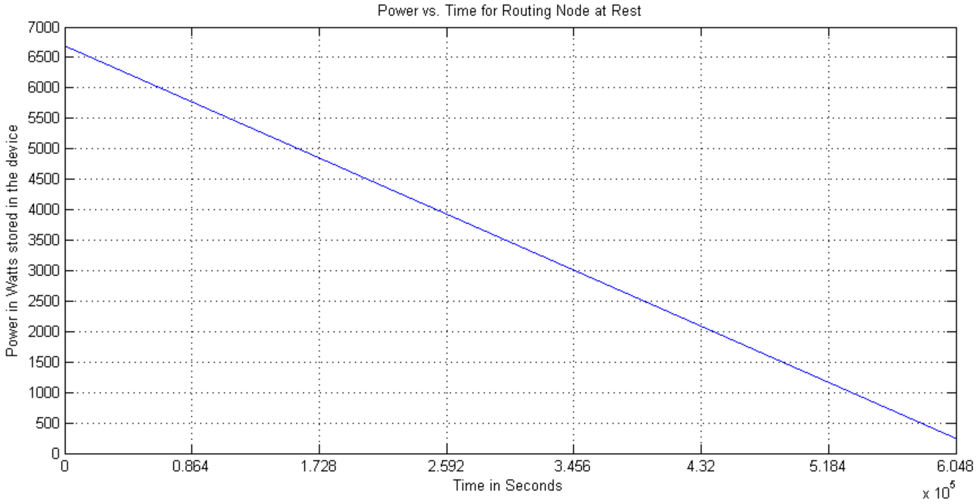

Figure 5.4 Power vs. time for routing node at rest.

At rest the routing node manages to stay active for a little over a week. This is fairly acceptable seeing as how much energy is consumed every time the router activates. However at work, it is predicted that the transmitter would be active every other second:

$$(1.8V * 200nA) * \frac{t}{2} + (1.8V * 16mA + 1.8V * 15mA + 1.8V * 1\mu A) * \frac{t}{2} \tag{5.4}$$

From this equation combined with the energy data we have we obtain Figure 5.5:

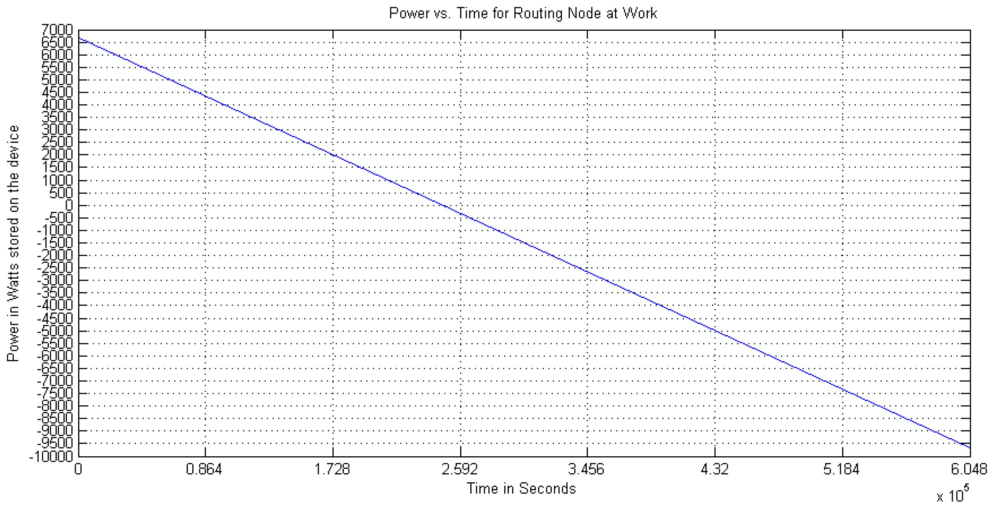

Figure 5.5 Power vs. time for routing node at work.

From this we can see that the routing node would only last for a little under three day at constant work. However it is highly unlikely that a person in a hospital would be under that much physical activity.

Just like with the temperature sensor, we can calculate a theorized week using the same predicted schedule with rehabilitation. To restate it the daily schedule for our theorized patient is; 3 hours of rehabilitation, 9 hours of sleep, and 12 hours of being awake and resting. The resulting values are that the sensor will transmit once every 2 seconds while at work, once every 5 seconds while at rest, and once every 10 seconds while the patient is sleeping. If we properly graph these times over the course of a week, so the patient sleeps from midnight to 9am, rests from 9am to 3pm, has rehabilitation from 3pm to 6pm, then rests again from 6pm to midnight the result is given in Figure 5.6:

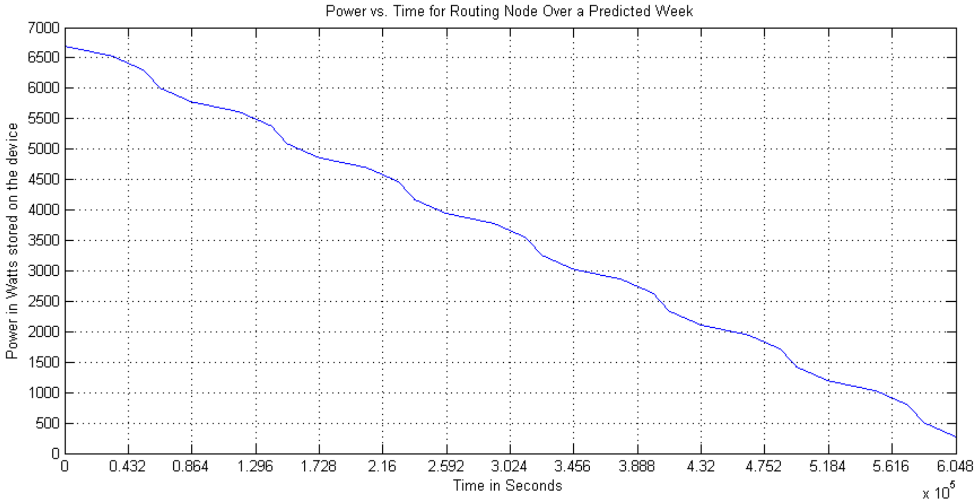

Figure 5.6 Power vs. time for routing node over a predicted week.

In the end the results for the temperature sensor are very promising. The battery allows the sensor to support the routing portion while the generators can keep the temperature sensor portion in check while resupplying the battery with more power to allow it to last longer. A look at the power supplies shows that the devices does mostly rely on the batteries though to power the transmission units and this is not what was intended when the device was first designed. Maybe if a lower cost transmission unit is found the button battery can be removed from the equation but until then this is the only way that we can guarantee the device to work well.

CHAPTER 6

CONCLUSION

This thesis discusses a number of methods for creating a wireless sensor that uses energy scavenging. We analyze the different energy scavenging methods such as vibration energy, thermoelectric energy, and photovoltaic energy. The conclusion is made that thermoelectric energy generators would not produce enough power for the device. However, even though vibration and photovoltaic energy generators both produce enough energy to power the device, they both have their flaws. Vibration energy generators require that the device is constantly in motion and photovoltaic energy generators lose a majority of their energy production capabilities at night or any time there is not sufficient light.

To counter act these flaws in the power production capabilities of the generators we introduce a rechargeable battery to the system such that the generators charge this battery. The excess power from the generators that is not used to power the device flows into the battery and charges it during the day. Then at night where this is no light and the patient is most likely not moving the battery kicks in and powers the device throughout the night. In actuality the algorithm is probably such that the battery is activated if the power flow from the generators drops below the required power to energize the device.

The next topic discussed is energy saving methods. We analyze each layer, covering how each layer can affect the energy required to power the device and what tradeoffs come from these methods. The application layer trades accuracy and output size, the routing layer trades delay for its energy consumption, the MAC layer also trades delay but also throughput and topology, physical layer trades connectivity and reliability, and the hardware layer trades response time and performance. We also analyze more complex methods such as voltage scaling, tunable compression and rate adaptation. By utilizing these methods to their fullest we can drastically reduce the energy consumed by the circuit.

The final topic that we looked at was an actual estimation and prediction of how much energy the generators could produce in what situations and whether they could support the devices on their own. It was seen that the transmission units for the data used much more power than the generators could produce and that they would need a small rechargeable battery that was already charged to keep it afloat. This is the biggest problem found in the design of the system. This small button battery was not in the initial design and it did not feel right adding it to the design. Perhaps it is necessary unless there is a much lower cost transmission unit out there that was looked over. If the battery is required the device can be designed so that the battery can be easily removed and replaced to keep the device working, however this grossly derails the device from its original idea of a completely autonomous device that would not need upkeep.

The final aim of this thesis is to gather the data and create some ideas for how to execute the final product. The point is to lay out the ground work. That has been accomplished to some extent in this thesis. The design with two generators and a battery seems very viable, and the network topology design that is discussed will also assist in the creation of an actual sensor network. The energy conservation methods are researched for their energy saving properties but they cannot be actually applied to the system without thorough testing first. The analysis shows that the generators cannot support the routing nodes on their own. This is a major flaw that needs to be overcome one way or another, either finding better generators or by finding more energy efficient transmission units. This research should help someone actually produce a useful sensor network some day.

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