Energy Harvesting and Power Management in Wireless Sensor Networks

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Abstract: Wireless sensor networks (WSNs) are employed in environmental monitoring, vehicle tracking, building management, body monitoring and other applications. Power sources for network nodes are often limited, which imposes restrictions on hardware resources and their use by the embedded software. This paper focuses on the study of energy harvesting techniques applied to powering wireless sensor network nodes. To test their efficiency, a fully configurable WSN architecture named Sparrow has been designed and implemented.

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1. INTRODUCTION

Wireless Sensor Networks (WSNs) or more generally Wireless Sensor and Actuator Networks (WS&ANs) are employed in a wide range of data acquisition, data processing, and control applications. Their advantages over traditional wired sensor and actuator networks include node mobility, increased reliability (due to availability of adaptive multi-hop routing), easier installation and lower deployment cost.

A WSN consists of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations. The development of wireless sensor networks was originally motivated by military applications such as battlefield surveillance. However, wireless sensor networks are now used in many civilian application areas, including environment and habitat monitoring, healthcare applications, home automation, and traffic control.

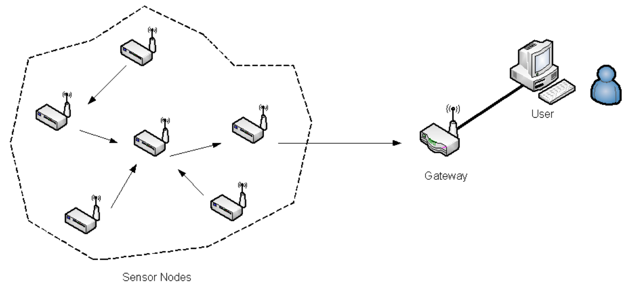

Fig. 1. Typical WSN architecture

Each node in a sensor network is equipped with at least one or more sensors. In addition to that, nodes must incorporate a microcontroller for data processing, some kind of wireless communication device, such as a radio transceiver and an energy source, usually a battery.

The size of nodes can be variable, ranging from tiny matchbox-size to large book-sized motes. Also, the cost of sensor nodes is variable, ranging from hundreds to a few euros, depending on the size of the sensor network and the complexity required of individual sensor nodes.

However, there are some characteristics that are shared by all wireless sensor networks, such as:

- Low-power architecture. Most wireless sensor nodes have limite finite or limited energy supply.
- Wireless communication. Nodes form single or multi-hop networks.
- Ability to withstand harsh environmental conditions
- Fault tolerance. The network employs hardware and software fault-tolerance algorithms.
- Node mobility. There is a wide range of applications, like body sensor networks, where nodes are not stationary.
- Communication failures. Due to the shared radio communication environment, packets can be lost.
- Heterogeneity of nodes. Not all nodes have the same functionality, measure the same parameters or even have the same hardware architecture.
- Large scale of deployment. Typical WSN monitoring scenarios can employ hundreds to thousands of nodes spread over a large area.
- Unattended operation. The network must be self-sufficient and self-reconfigurable.

The constraints in size and cost of sensor nodes can lead to corresponding constraints on resources such as energy, memory, computational speed and bandwidth. WSN nodes have specific hardware characteristics and limitations. Most WSN nodes have limited available energy: some rely on batteries and some employ environmental energy harvesting techniques such as solar panels, wind- or vibration-powered generators or thermoelectric generators. Therefore WSN nodes tend to be small embedded systems with few processing resources and low bit rate, low range radio links. Cost and size restrictions impose similar constraints.

In this paper we present a new wireless sensor network architecture named Sparrow. It is comprised of multiple low-cost motes that employ the concepts of energy harvesting in order to achieve total independence from conventional energy supply sources.

2. ENERGY STORAGE SYSTEMS FOR WIRELESS SENSOR NODES

Wireless sensor nodes are designed to be low-power devices that can function for years in remote areas without human intervention. Therefore, the means through which they store and use energy is an important aspect in WSN design.

Also of great importance are the power supply systems in wireless sensor nodes. A poorly designed power supply can end up consuming more energy than the node itself or be too expensive to be deployed on typical sensor networks of thousands of nodes.

Power management in wireless sensor networks can be formulated as a simple supply and demand problem: given a limited (and often variable) supply of energy, the node must adapt its consumption to fit the required power profile. However, the problem is rarely this simple, as the form of energy provided by the power supply is rarely optimal for the load. It is because of this fact that no single power supply system is optimal for wireless sensor nodes, even though they exist in a wide variety.

For our study, we focused on two major energy sources available on the market. The first and immediate choice was to use common electrochemical batteries. They have a finite supply of energy, so the system must be designed to operate in such a way that its lifetime is maximized.

The second approach is somewhat non-conventional and is based on the concept of energy-harvesting, that is, scavenging energy from regenerable sources that are universally available in the environment. When these techniques are employed, the power source typically has a finite power limit. If power greater than this value is required at any time, some form of power-conditioning is needed.

This is often the case for wireless sensor network nodes, due to their low average power but relatively high peak power requirements. Of course, the cost and inefficiency of the secondary storage system must be included in the design of the network node.

2.1 Batteries

For many applications, mains power is not an option, and batteries are used. Many types of batteries are available nearly worldwide and avoid many of the hardware costs associated with the use of mains power. However, they require design considerations.

Battery parameters such as the lifetime, capacity and speed of charge are directly influenced by its chemistry. Usually, when it comes to battery charging, the total time to reach full capacity is in direct proportion with the milliamp hour (mAh) capacity of the battery.

For example, if a source is rated at 400 milliamps, charging an ideal 400 mAh battery would take 400/400 = 1 hour (C), while charging a battery of half capacity would take 200/400 = 0.5 hours (0.5C). In all actuality however, charging a battery actually requires more than 1C to fully recharge because of its imperfections.

As the demand increases for wireless sensors that can be deployed and remain operable indefinitely, the efficiency of battery charging becomes crucial. First on the list of design considerations for battery-operated equipment is a finite lifetime, which requires that batteries be replaced or recharged.

For example, the widely used Mica2 mote uses a 38.4 kbps radio with a range of ~80 meters in ground-level, line-of-sight communication. Powered by two AA batteries, it can run for a few hours in 100% duty cycle, or a few months when activated by a threshold detector with very infrequent events. With some external circuitry and a solar panel, the batteries can be recharged each day for significantly extended operations. Due to the limited number of recharge cycles, the battery will require replacement after one to two years.

Unfortunately, such recurring maintenance cost is likely to become very expensive or prohibitive if it must be done for thousands of deeply embedded nodes, which are likely to be difficult or expensive to access after deployment.

Battery use and recharging is a proven technology and has been used extensively in WSN node implementations. Because of this and of the shortcomings that were enumerated in the above paragraphs, this paper focuses on finding and researching alternate technologies that can be used for energy storage at node level. One of the most promising technologies is presented in the next section.

2.2 Super-Capacitors

A typical electrolytic capacitor is in the range of one up to several thousand or ten thousand microfarads. For most small electronic applications that utilize energy harvesting, this is too small of a capacitance to store enough energy.

Several capacitors could theoretically be connected in parallel to increase the capacitance, but the size of such a device would be impractical. Therefore, super-capacitors are often considered instead of electrolytic capacitors.

Super-capacitors, also referred to as ultracapacitors or electrochemical double layer capacitors, are different from the conventional electrostatic and electrolytic capacitors because they contain an electrolyte which enables the electrostatic charge to also be stored in the form of ions. They are governed by the same fundamental equations as conventional capacitors, but utilize higher surface area electrodes and thinner dielectrics to achieve greater capacitances.

Depending upon the application, the equivalent series resistance, or ESR of the capacitor can have a big impact on the voltage fluctuation across the capacitor during charging, as well as the current leakage rate out of the capacitor over extended periods of inactivity.

As such, the maximum power that a super-capacitor can supply a given circuit can be expressed by:

$$P_{max} = \frac{V^2}{4R_{ESR}} \tag{1}$$

where R_{ESR} is the equivalent series resistance of the capacitor.

By keeping the R_{ESR} small, super-capacitors are able to achieve relatively high power densities. Despite greater capacitances than conventional capacitors, super-capacitors cannot yet match the energy densities of mid to high-end batteries.

However, in the field of wireless sensor networks where node consumption is in the range of tens of milliamperes, such large energy densities are not necessary and the advantages of using such a capacitor far outweigh the inconveniences. Also, the problem of designing efficient charging circuits for batteries (that they themselves need power to operate) is non-existent in the case of capacitors.

Compared to the 1000 typical charge-recharge cycles that a rechargeable battery offers, a typical super-capacitor offers more than half a million charge cycles and a 10-year operational lifetime until its capacity is reduced by 20%. At this point 80% of the useful energy is still available because the ESR is still very low unlike a battery whose useful energy drops to 50% at this point because the higher ESR causes premature end of life. Therefore, by designing the node to operate on 50% energy capacity, the operational lifetime can be pushed out to over 20 years.

3. ENERGY HARVESTING

Energy Harvesting is the process by which energy from the surrounding environment is captured and stored. In recent years the term has been applied mainly to sensor networks, where autonomous sensor nodes employ this process to replenish their energy resources. When applied to our architecture, energy harvesting increases the robustness and availability of the system, making it energy-independent.

Harvesting Technology	**Power Density**
Photovoltaic Cells(maximum illumination)	$15mW/cm^3$
Piezoelectric (cantilever structure)	$330\mu W/cm^3$
Vibration(kitchen appliance)	$116\mu W/cm^3$
Thermoelectric($\Delta t = 10 \deg C$)	$40\mu W/cm^3$
Acoustic noise ($100dB$)	$960nW/cm^3$

Table 1. Most common energy harvesting sources

We can approximate the sensor network with a closed energy system where each node has a total energy production rate $P_p(t)$ and a total energy consumption rate $P_c(t)$ (Rahimi 2003). Therefore, the excess of harvested energy by the node at any moment can be estimated by the following formula:

$$E(t) = \int_0^t (P_p(t) - P_c(t))dt \tag{2}$$

A node is deemed energy-independent if its excess energy satisfies the following formula:

$$E(t) > 0, \forall t > 0 \tag{3}$$

A variety of sources for energy harvesting have been researched, such as solar power (Alippi 2008), thermal (Mitcheson 2010), RF (Fahrinolt 2009) and kinetic energy (Roundy 2003). All of the energy sources stated above have small energy density values compared to more classic energy sources, such as batteries. In the past, the use of radio transceivers often implied large amounts of power consumption. This is no longer the case today, as recent advances in the design of low-power electronics and energy storage have made wireless sensor networks a prime candidate for the successful integration of energy harvesting techniques.

3.1 Thermoelectric Harvesting

Thermoelectric energy harvesting is based on the Seebeck effect, in which a thermal gradient formed between two dissimilar conductors produces a voltage. At the heart of the thermoelectric effect is the fact that a temperature gradient in a conducting material results in heat flow; this results in the diffusion of charge carriers. The flow of charge carriers to the low-temperature region in turn creates a voltage difference. The Seebeck effect is a phenomenon that occurs when a voltage (V) is induced in proportion to an applied temperature gradient (ΔT) related by:

$$V(T) = \alpha \Delta T \tag{4}$$

where α is the Seebeck coefficient. This relationship is exploited most often for the purpose of temperature measurements, but can also be used on a larger scale to develop a high enough voltage and current output to run different devices and sensors or even to charge a small battery.

A thermoelectric generator (TEG) is easily modeled as a DC voltage source in series with an internal resistance. The power delivered is maximized when the load resistance or impedance is equal to the internal resistance of the TEG.

We can express the generated power of an ideal TEG related to the temperature drop between its two plates by the following equation:

$$P_{TEG}(T) = \frac{(\alpha \Delta T)^2}{R_{TEG}} \tag{5}$$

where R_{TEG} is the internal resistance of the generator that depends on its dimensions and material properties.

In order to determine if TEG harvesting can accomplish the task of powering a sensor node, we measured the power output of a TEG circuit on a static resistive load that was used to simulate a wireless sensor mote.

As predicted by the Seebeck effect law, the voltage drop across the load was measured to be in direct proportion to the temperature variation. A maximum voltage of $1,065V$ was achieved for a temperature gradient of $37.7C$.

The power output of the system, as a function of the temperature differential is plotted in Figure 2. The maximum measured output for the temperature gradient mentioned earlier was $1.6mW$

A second experiment focused on measuring the output power of the generator for a variable load. For this, the temperature difference between the hot and the cold plates of the thermoelectric element was kept constant at 35 degrees Celsius. The load resistance was varied while measuring the values for current and voltage.

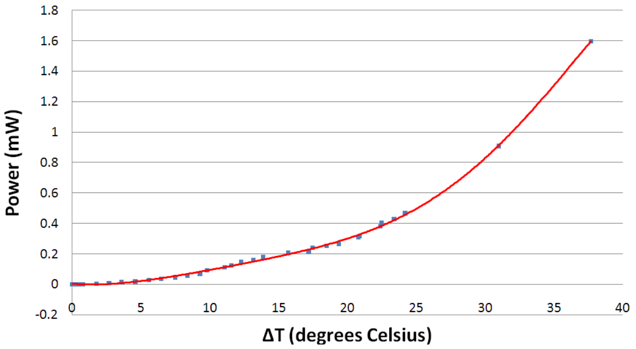

Fig. 2. Total power output of the TEG as a function of temperature differential. The power measurements were taken on a fixed resistive load.

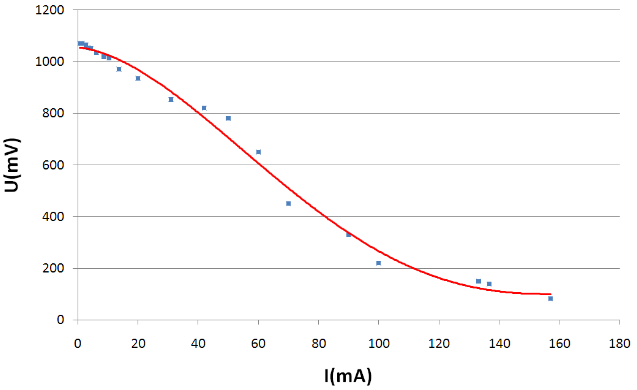

Fig. 3. Voltage drop across the variable load resistor depending on the circuit current.

The purpose of this experiment was to determine the circuit load that yields maximum power from the generator. This information is useful in the design of a circuit that uses the energy from the TEG to charge a battery or a super-capacitor. Such an optimal charger circuit can be made to track this maximum power point and give the best performance in any given situation.

The maximum power achieved at a temperature differential of 35 degrees Celsius was $39mW (0.78V/50mA)$. While this is not enough to continuously power a Sparrow WSN node (instantaneous power consumption can reach a maximum of 66mW), it is more than enough to ensure a partially-on power scheme in which the node periodically wakes up from a sleep state, takes measurements and relays that information to the sink node, before going back into sleep mode.

The advantages of thermoelectric scavenging are that they have a very long operational lifetime, due to the fact that they have no moving parts and they have no materials that must be replenished.

One downside to thermoelectric energy conversion is low efficiency which is currently less than 10%. The development of materials that are able to operate in higher temperature gradients, and that can conduct electricity well without also conducting heat (something that was until recently thought impossible), will result in increased efficiency.

3.2 Photovoltaic Harvesting

The most common energy scavenging technique is the use of photovoltaic cells to obtain power from ambient light, usually sunlight. For locations in which the availability of light to network nodes can be guaranteed to a sufficient degree, and for which mains and primary battery supply is impractical, this can be an excellent energy source.

The electrical power that can be extracted from a photovoltaic cell is proportional to the area of the cell and the intensity of the incident light. The terminal voltage of the cell resembles that of a semiconductor diode and is relatively insensitive to changes in light intensity, while the output current is directly proportional to light intensity.

By analyzing the data from the Table 1 we can see that solar cells offer the best efficiency while at the same time being a environmentally-friendly power source.

In order to measure the efficiency of photovoltaic harvesting, we used $2V, 200mA$ polycrystalline silicon solar cells that were subjected to different illumination conditions. Energy generation was measured for both static and variable resistive loads.

The first experiment involved exposing the cell to different illuminations and measuring its voltage-current characteristic. Three light intensities were chosen: direct sunlight, light from a 100W light bulb placed directly over the cell and the ambient light of a dim room. Current and voltage across the variable load resistance were measured and the characteristics can be seen plotted in the figure below.

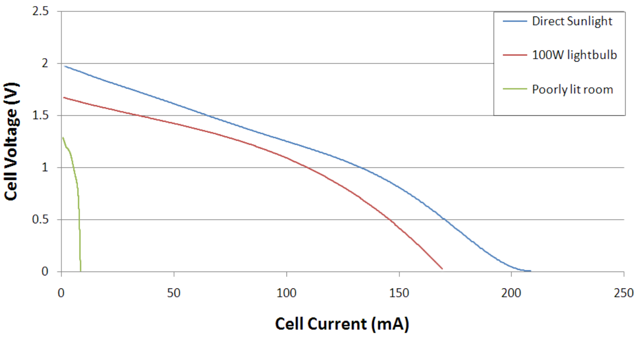

Fig. 4. Cell voltage on a variable load for different illuminations of a photovoltaic panel.

Several observations can be made from the figure above.

First, it is clear that a solar panel behaves as a voltage limited current source (as opposed to a battery which is a voltage source). Second, there exists an optimal operating point at which the power extracted from the panel is maximized (Brea 2009). Finally, as the amount of incident solar radiation decreases (increases), the value of the circuit current also decreases (increases).

Due to its current source-like behavior, it is difficult to power the target system directly from the solar panel, since the supply voltage would depend on the time varying load impedance. Hence, an energy storage element, such as a battery, is used to store the energy harvested by the panel and provide a stable voltage to the system.

Peak power graphs for each case can be seen in the plot below.

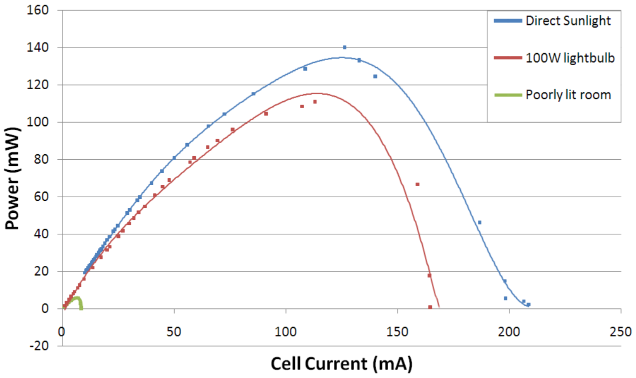

Fig. 5. Cell voltage on a variable load for different illuminations of a photovoltaic panel.

The second experiment intended to measure the total energy that can be harvested with a single PV cell on the duration of a single day. To achieve this, the cell was fixed in a Soth-facing location and the voltage drop across a load resistor was sampled once every 60 seconds. The sampled voltage values were averaged each half hour and the value was logged in the system's memory.

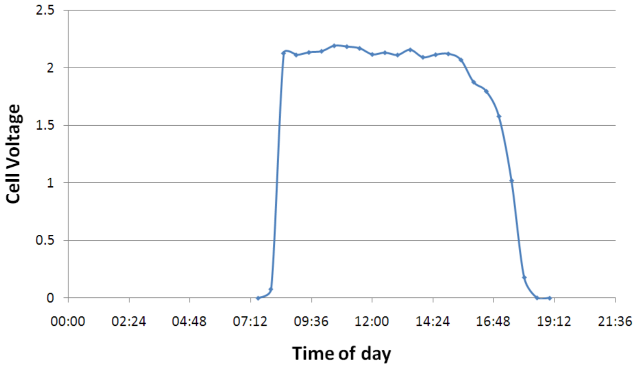

Fig. 6. Photovoltaic cell voltage drop measured in the course of one day on a fixed resistive load

We came up with an average $261mW$ over the course of one day, taking into account that the solar cell is placed into an area of moderate to high illumination, such as a window frame. We can calculate the total energy harvested in one day by the solar cell:

$$E_{harvest} = P \times t = 261mW \times 24h = 22600Joule \qquad (6)$$

The Sparrow node drains a maximum of $30mA$ at $3V$ from the power supply. By taking also into account the sensors and additional circuitry with an additional $10mA$ at the very most, and implying that no software sleep algorithms are implementes, the total energy required for the node to run without pause for the duration of a single day will be:

$$E_{spent} = U \times I \times t = 3V \times 40mA \times 24h = 10368Joule (7)$$

This proves that, given enough storage capacity and enough incident radiation, solar energy harvesting can power a node for an indefinite amount of time. Taking into account the fact that nodes employ power management in the software stack, alternating between long periods of sleep and only short intervals when active, there is actually excess energy produced. This additional energy is stored in the battery pack to be consumed during the night or on clouded days.

4. THE SPARROW WIRELESS SENSOR MOTE

In this section we describe the hardware implementation of our sensor motes. A sensor mote is a node in a wireless sensor network that is capable of performing some processing, gathering sensory information and communicating with other connected nodes in the network.

Typical wireless sensor node architecture WSN nodes have specific hardware characteristics and limitations. Most WSN nodes have limited available energy: some rely on batteries and some employ environmental energy harvesting techniques such as solar panels, wind- or vibration-powered generators or thermoelectric generators. Therefore WSN nodes tend to be small embedded systems with few processing resources and low bit rate, low range radio links. Cost and size restrictions impose similar constraints. A typical architecture of a sensor node is shown below.

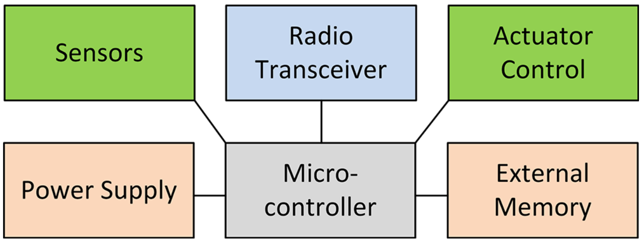

Fig. 7. Typical wireless mote hardware architecture

The Sparrow v2 wireless sensor mote Sparrow ? is a wireless sensor network architecture that has been built as a research platform for the energy harvesting techniques described in the previous chapter. It was also used to deploy and test a series of wireless applications including IEEE 802.15.4, 6LoWPAN and ZigBee networks.

It is built around the Zigbit A2 module from Atmel which incorporates a low-power 8-bit RISC microcontroller connected to a 2.4GHz 802.15.4 radio transceiver. In order to increase versatility, the microcontroller is linked to an extended sensor bus that can accommodate up to three different types of analog and digital sensors.

Although the mote has very low power consumption and can function for long periods of time on a single battery charge, we designed the node for total energy-independence. Additional components for power management and energy harvesting were needed and we opted for the architecture presented in the diagram below.

The voltage from the energy harvester is used to charge the battery pack by the first stage DC-DC converter. Then, battery voltage is supplied at a stable level to the node's main circuitry. For power management purposes, the node also needs to continuously monitor the voltage and the current drawn from the battery pack, which is achieved by the energy measurement module.

The main challenge in the design of the Sparrow nodes was the power management and energy harvesting circuit.

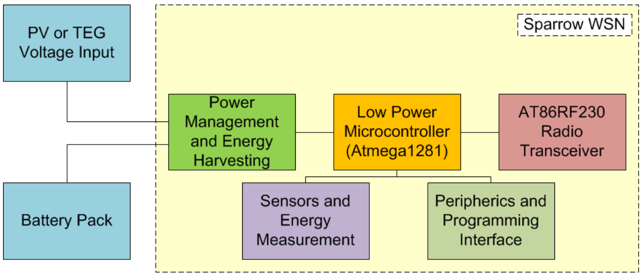

Fig. 8. Sparrow v2 architecture

Its main function is to collect energy from an attached photovoltaic cell of thermoelectric generator and continuously charge a super-capacitor. When the charge level on the capacitor exceeds a predetermined threshold, the WSN node is powered.

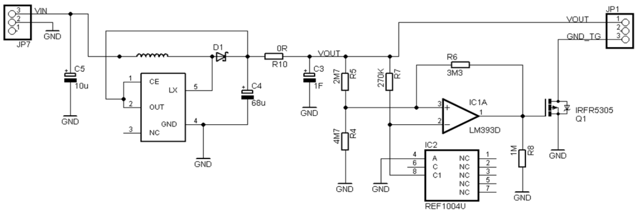

Fig. 9. Schematic of the energy harvesting and power management unit

The circuit is comprised of two separate sub-systems: the step-up switching regulator and the voltage monitoring and control circuit. Energy harvested by the photovoltaic cell or by the TEG can vary and is in direct relation to the environment condition. For example, the voltage output of the PV panel can be anything between 0V and 2V, depending on the amount of solar radiation the panel receives during a day. The same applies to the thermoelectric generator.

As the WSN node electronics operate at minimum 2.2V, the voltage generated by energy harvesting is not high enough. Therefore, a switching converter was used to step-up the gathered voltage to a fixed value. This was accomplished using the NCP1402 high-efficiency micropower regulator from On Semiconductor. This device is designed to start at a minimum input voltage of 0.8V and reliably operate down to 0.3V while keeping a fixed output voltage value of 3.3V. The output voltage from the switcher is used to slowly charge a 1F double layer super-capacitor which acts as a power supply for the rest of the node's electronics.

The monitoring circuit's role is to power on and off the WSN node, depending on the amount of charge stored in the capacitor. It achieves this function by continuously monitoring the capacitor voltage.

Because of its continuous functioning, the circuit must be very low power and operate over a wide supply voltage range. The circuit in Figure 9 uses the MCP6542 voltage comparator, which has a typical operating current of 600nA for the monitor function. The MCP6542 is used with the threshold and hysteresis setting resistors R4, R5, and R6, and the LM385 voltage reference to control a FET switch, Q1, to turn on power to the MCU circuitry. The FET is on when the voltage on C3 is greater than 3V and off when the voltage on C3 is less than 2V. Calculating the capacitor size for energy storage requires an estimate of the current flow in the circuitry, what is the voltage change on the capacitor and how much time is required complete a task. For example, when the node is active, the Sparrow circuitry requires about 23mA for continuous operation.

The time the circuitry can operate continuously for a change in C3 capacitor's voltage from 3V to 2V is calculated from:

$$T = \frac{C\Delta V}{I} = \frac{1F \cdot 1V}{0.023A} \approx 44s \qquad (8)$$

This short functioning time can be extended in two ways: by increasing the value of the capacitor and by rigorous software power management on the node.

For example, a 100F super-capacitor can easily power the node in continuous mode for 100 times the amount of time calculated above, which means that the node can function for about 73 minutes without any sunlight.

The second approach is even more effective and relies on the observation that in most WSN application scenarios a node does not need to stay on 100% of the time. This behavior is called beaconing and implies that the node stays in sleep state for a period of time and wakes up on regular intervals to measure sensor data and relay it to the sink node.

By using this behavior, large amounts of energy that would have otherwise been wasted on powering the node, can now be stored for future use in the capacitor, thus increasing the system's lifetime.

For example let us presume that a Sparrow node uses a beaconing scheme and wakes up every 30 minutes for about 1 second. Taking into consideration that the node has 6uA of current consumption in sleep mode and 23mA during wake-up, the total functioning time of the node can be increased from 44 seconds to 2.2 hours which is an improvement of almost 200 times.

By combining the two approaches, of increasing the capacitor size and beaconing, the Sparrow node can function for an indefinite amount of time on the energy gathered from its surrounding environment.

5. CONCLUSIONS

This paper has analyzed the applicability of energy harvesting to a wireless sensor mote. Two of the most promising energy sources were researched: thermal and solar energy scavenging. All of the three sources were analyzed in terms of the total amount of energy produced and their ability to ensure the continuous functionality of a sensor node.

We found that solar energy offers the best results both in terms of the quantity of harvested energy and in the amount of instantaneous power the system can generate when subjected to full illumination.

Energy storage was also researched and we found that usual rechargeable batteries are sub-optimal when used on a long-term service-free architecture as wireless sensor networks. Instead we focused on super-capacitors and their ability to store large amounts of charge over long periods, without any significant loss of performance over time.

A wireless sensor network infrastructure named Sparrow was built to test the research concepts and to measure experimental data.

One of the future research goals for this project is testing the network in real life conditions over long periods of time. For this, the nodes that are equipped with energy scavenging capabilities will be deployed in a remote area (i.e. forest, urban area, building) and performance measurements will be taken. Different power management schemes and algorithms can also be deployed to aid the total system up-time.

6. ACKNOWLEDGEMENTS

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