# Thermal Energy Harvesting for WSNs

Xin Lu
Department of Computer Science
Loughborough University
Leicestershire, UK
X.Lu2@lboro.ac.uk

Shuang-Hua Yang
Department of Computer Science
Loughborough University
Leicestershire, UK
S.H.Yang@lboro.ac.uk

***Abstract*— Because of the recent developments in both wireless technologies and low power electronics, wireless devices consume less and less power and are promising the possibility to operate continuously by using energy harvesting technologies. The interest in Wireless Sensor Networks (WSNs), powered by environment energy harvesters, has been increasing over the last decade, especially those using thermal energy harvesting. In this paper, a low temperature thermal energy harvesting system, which can harvest heat energy from a temperature gradient and convert it into electrical energy, which can be used to power wireless electronics, is proposed. A prototype based on three subsystems is presented to extract heat energy from a radiator and use it to power ZigBee electronics. High efficiency and a long system lifetime are two of the main advantages of this design. The experimental results show that a maximum of 150mW power can be harvested by the prototype and the system can continue to operate normally when the harvesting voltage is as low as 0.45V. Theoretical calculations suggest that by placing the two AA batteries by proposed thermal energy harvesting system, a ZigBee Wireless Radiator Valve can operate for more than eight years.**

***Keywords—Keywords*—Energy havesing, thermal energy harvestign system, thermoelectric, wireless sensor network, ZigBee, DC-C converter, power mangement.**

## I. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) technology is developing fast, with corresponding decreases in cost, enabling micro and wireless sensor systems to be rapidly developed. Nowadays, some very low power wireless productions have entered the marketplace and the large-scale deployment of such networks is being considered to carry out complex tasks without human intervention. However, power supply represents perhaps the most challenging technological hurdle still to be overcome in the widespread development of Wireless Sensor Networks (WSNs). Normally, batteries are the dominant energy source for WSNs but they are not the optimal choice for wireless electronics, because their lifetime is limited and battery leakage can pose serious environmental pollution. Therefore, the aim of developing completely self-powered wireless electronics has received significant interest over the last decade. Energy harvesting techniques are considered as a promising technology to achieve this. When deploying a WSN, the sensor nodes are placed in a variety of locations, some of which have ambient light and other have ambient thermal gradients. Recent developments in thermoelectric (TE) materials and structures have lead to renewed interest in TE power generation, which offers a unique and attractive alternative to batteries due to its heat energy harvesting capabilities.

### A. *Existing Works*

A simple TE generator is made by heating one face of TE module, and cooling the other face causing an electrical current to be generated by connected a load to the end points of the TE module. This behavior is described as the Seebeck effect, and was discovered by Tomas Seebeck in 1821. A TE generator has demonstrated attractive characteristics such as a long life cycle, no moving parts, simple and high reliability. However, its low efficiency is a big drawback that has continually prevented the widespread commercial application of this technology. Current TE materials can only convert a maximum of 5-6% of the useful heat into electricity. However, some significant researches [1, 2, 3, 4] is being carried out to develop new materials and module constructions, which promise harvesting efficiency of more than 10%.

Nowadays, more and more investigations are moving into the thermal energy harvesting area and there are some successful industrial applications using TE generators. The Seiko Thermic watch [5] is considered to be the first application of thermal energy harvesting to a consumer product. It uses a TE generator to convert body heat into electrical energy that is used to drive the watch. With about a 1 K temperature gradient between the wrist and the environment at room temperature, 22 μW can be harvested by the generator. Moreover, this energy not only drives the watch but also charge a 4.5mAh lithium-ion battery. Kocoloski et.al [6] suggests TE and thermionic generators as two potential ways to retrieve electrical energy from waste heat in industrial applications. To test this concept, a prototype using a thermionic device was built to extract waste heat energy from a furnace at a glass manufacturing facility. The results showed that nearly 1/3 of the energy available in the exhaust gases could be converted into electricity. Eakburanawat [7] developed a TE battery-charge with a microcontroller to generate electrical energy using waste heat. In this design, a SEPIC DC-DC converter was applied and controlled by a microcontroller with a maximum charging power of 7.99W. The conversion efficiency is approximately around 15%. In [8] the authors proposed a TE generator in stoves to produce electric energy, which could be used to generating light. A prototype generator, which is expected to cost around $30 if produced in large enough quantities, was developed. In their work, several design considerations such as selecting a proper TE module and designing heat sink were proposed. Moreover, there is also some research which focuses on designing a high efficient TE

978-1-4244-6588-0/10/$25.00 ©2010 IEEE

generator for WSNs. In [9] the authors developed a thermal energy harvesting system, which can harvest thermal energy from sunlight. In order to enhance its efficiency, eight TE modules were placed in a small greenhouse. 40mW power could be generated from such a TE generator when it is placed on a 200$^{o}C$ surface. Mateu [10] proposed a thermogenerator system to harvest energy from small temperature gradients between the human body, and the ambient environment. The power generated by this TE generator is often as low as 0.3V, which is not suitable for many practical applications. To supply a wireless communication module and to charge an energy storage element, a charge pump IC with a step up DC-DC converter was employed to boost the input voltage. The authors of [11] proposed a low input voltage converter for TE generators. It could self-start operation when the input voltage is as low as 300mV. Xin [12] proposed a highly efficient solar energy harvester for ZigBee electronics. The platform can autonomously and simultaneously harvest energy from solar energy source while performing maximum power point tracking. To prolong the lifetime of the system, a power management design with two buffers was employed. These systems have made a significant contribution to the development of a thermal energy harvester. However, these existing studies have not taken on board all the necessary considerations for the design of a high efficient and long lifetime TE generator for WSNs.

### B. *Features of the Proposed System*

Basically, a permanent harvesting system with high efficiency, simple and compact construction, is considered as an idea battery replacement for WSNs. Based on these concepts, this paper presents a low temperature TE generator designed by considering various design characteristics required to satisfy the power needs of wireless sensor nodes. In order to show the performance of the prototype, in terms of thermal energy harvesting efficiency, the proposed TE generator was used to replace the batteries required to power a ZigBee Based Automatic Radiator Valve (ZBARV). In this work, the following contributions have been carried out.

- The architecture of the TE generator is designed to reduce the system's complexity.
- Various design considerations for designing a high efficient TE generator have been presented.
- A high efficient heat sink has been designed.
- The best position to locate the TE generator on the radiator has been found
- To enhance the system's efficiency, an improved DC-DC converter subsystem has been designed to convert low harvesting voltages from the TE modules.
- A functioning power management subsystem has been designed to prolong the lifetime of the system. To reduce the energy consumption of the system, a dynamic power management algorithm has been developed.

The rest of the paper is organized as follows. In Section 2, the design considerations and implementations of the thermal energy harvesting system are described. Ways to improve energy harvesting efficiency and the system's lifetime are considered. Section 3 provides a description and discussion of the proposed system. Finally, a conclusion and proposals for some future works are presented in Section 4.

## II. System Design and Implementation

Normally, there are three steps in determining the design of a thermal energy harvesting system for WSNs. The first design consideration in designing a successful TE generator is to determine the electrical characteristics of the target system. In this paper, a ZBARV is considered as the target system. A ZBARV is a ZigBee based home automation system [13] that can regulate a motorized radiator valve to control the central heating radiator for normal household use. ZigBee technology is an exciting new area of WSNs, which is defined by IEEE standard 802.15.4. ZigBee devices have some significant characteristics such as limited computation ability, sensing communication and power. A Jennic's JN5139 microprocessor [14] was employed as a control MCU in this system. The electrical characteristics of ZBARV are described in Table I. The longevity of the whole system is around one year or less and is powered by using two AA batteries. This restriction means that the batteries must be changed at least every year. This is the main hurdle that must be overcome if ZBARV is to be used in a normal house.

TABLE I. ELECTRICAL CHARACTERISTICS OF ZBRVA

| Parameter | Value |
|---|---|
| *Supply Voltage* | *2.7-3.3V* |
| *Working Current* | *60mA* |
| *Sleeping Current* | *10uA* |
| *Working duration* | *20 Seconds/hour* |
| *Sleeping duration* | *3579 Seconds/hour* |

Determining the energy source and energy density in the environment where the harvesting system is located is the second consideration. In this paper, a radiator is the heat source and the temperature gradient between the radiator and the environment can be harvested by a TE generator. Assuming the radiator's normal temperature is around 50$^{o}C$ and the room temperature is a relatively low, 21$^{o}C$, the energy density is 1.6KW per cubic meter based on Fourier's law. The last design consideration is the transfer efficiency of the TE module. As indicated in the previous section, the maximum efficiency of a state-of-the-art TE module is about 5%. Hence, means to enhance the harvesting efficiency is an essential part in the design of a good TE generator.

The conceptual design of the thermal energy harvesting system for the ZBARV is depicted in Figure 1. The water is assumed to flow from side A to side B. The motorized valve is installed on side A to control the input of water. The radiator emits a large amount of thermal energy when the valve is open. The temperature gradient between the radiator and air can generate electric energy that is used to drive the ZigBee product by attaching the TE generator to the radiator.

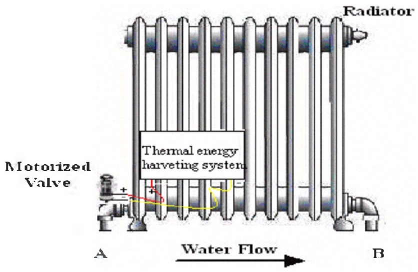


Figure 1. A scenario diagram of TE generator

By considering all aspects of ambient power sources in the light of the special characteristics of ZBARV, a thermal energy harvesting system was designed. Figure 2 depicts the general architecture of the thermal energy harvesting system, which is composed of three subsystems: the thermal energy harvesting subsystem, the DC-DC converter subsystem and the power management subsystem. In the proposed system architecture, three primarily steps are achieved to harvest thermal energy for the target system. The thermal energy harvesting subsystem harvests thermal energy and converts it into electrical energy. Then the output of the TE generators is connected to the DC-DC converter subsystem to increase the available output voltage in order to supply the ZigBee chips and to charge some energy storage elements. Synchronously, the harvested energy is efficient distributed by the power management subsystem.

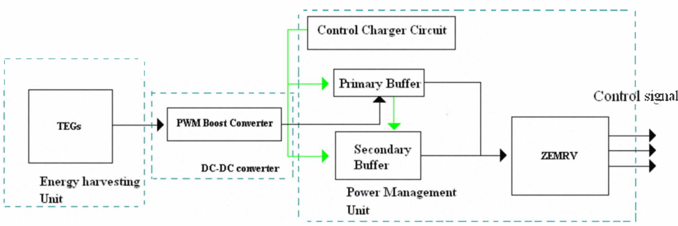


Figure 2. Fuction diagram of a Thermal Eneryg Harvesting System

### A. Thermal Energy Harvesting Subsystem

The harvesting efficiency is a critical factor that limits the use of any thermal energy harvesting system. A highly efficient system is the basic requirement for a successful harvesting system design. Basically, the efficiency of the TE generator is dependent on two factors: the efficiency of the TE module and the heat temperature level, which can be conducted through the modules. Hence, the performance of a TE generator can be enhanced by increasing the TE material capability, maintaining a large temperature differential across the TE module; and producing high thermal flows through the system.

The use of a good TE Module usually plays the most important part in the design of a successful TE generator. The first design process of a thermal energy harvesting subsystem is to select a proper type of TE module. TE materials and module construction are considered as the two primarily considerations in selecting the appropriate module. In the nature world, there are many materials which can produce power from temperature differences and them varying in cost, operation temperature and efficiency. Micropelt utilizes Bismuth(Bi), Antimony(Sb), Tellurium(Te) and Selenium(Se) are compounds that have the best material properties with operating temperature around room temperature and up to $200^{o}C$ [15]. Furthermore, the price of $Bi_2Te_3$ material is quite low because it is the most common material used in Pelteir coolers. Hence, this type of TE module was chosen as the thermal energy harvester for this design. On the other hand, module construction affects the maximum power and the voltage/current characteristics of the system. A TE module is typically composed of hundreds of TE elements, which are formed by P-type and N-type semiconductors, connected in series electrically and in parallel thermally between two ceramic layers. The voltage generated is proportional to the number of elements since they are combined electrically in series. An interesting observation from [8] showed that the power increases as the thermoelement leg length decreases. This means that a higher power module has a more compact construction and requires less material than a lower power module. Moreover, the test result from [16] illustrates that as the surface area of the TE generator is increased, the power generated increased in parallel. By considering all these considerations, the Taicang TE cooler company's $Bi_2Te_3$ TE module TEC1-12709 [17] was been chosen as the TE module. The physical properties are shown in Table II.

TABLE II. PHYSICAL PROPERTIES OF TE MODULE

| Parameter | Value |
|---|---|
| *Dimensions* ($w \times l \times h$) | $30 \times 34 \times 3.2$ *mm* |
| *Maximum temperature difference* | *77Kelvin* |
| *Number of thermocouple junctions* | *127* |
| *Device resistance* | *3.78 ohms* |
| *Resistivity* | *137 ohm cm* |

The temperature difference across the module is another significant factor in determining the efficiency of the whole harvesting system. In an environment in which a huge thermal gradient is present, the whole harvesting efficiency is raised whist it drops where there are only small differences in temperature values. In order to maintain a large temperature difference across the module, a hot side heat exchanger and efficient heat dissipation on the cold side of the TE generator are needed. A good thermal conductor material such as metal is considered as an ideal heat exchanger for heat transfer. On the hot side of the module, a piece of aluminum plate has been chosen as the hot side heat exchanger. On the cooling side, because heat transfer is limited by air-cooling, a high efficient heat sink is needed. A schematic diagram (Figure 3) shows the layout of the thermal energy harvesting subsystem.

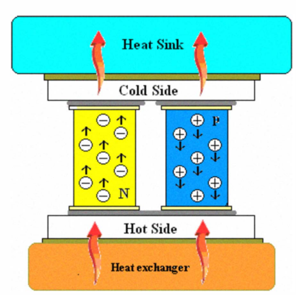


Figure 3. Thermal Energy Harvesting Subsystem

In order to choose a highly efficient heat sink as the cold side heat dissipation device, three types of heat sinks: a copper heat sink, an aluminum heat sink and a heat pipe type heat sink are compared in this paper. To test the heat transfer efficient, the same TE module is attached to three different types of heat sinks and tested in the same environment where the room temperature is 20 $^oC$ . The results of the experiments are summarized in Figure 4. From the graph it can be seen that the generated voltage of the TE module for the three different heat sinks varies, because the heat sink's ability to remove energy from the cold side differs. The heat pipe type heat sink is the most efficient one. Therefore, an Auras's 3 Heat pipes [18] heat sink is employed as the cold side heat sink.

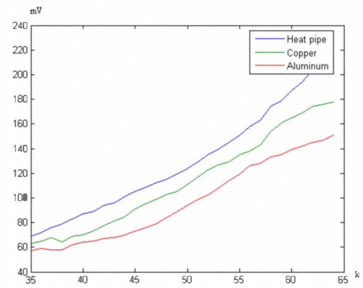


Figure 4. The comparison result of three Heat sinks

Furthermore, the ambient air temperature around the heat sink is a crucial factor affecting the heat conductivity of the heat sink. There are three ways, to reduce the temperature of the air surrounding the heat sink, which are considered in this work. When the heat sink is close to the heat source, the temperature of the air around the heat sink is higher. This reduces the heat transfer capability of the heat sink. Thus, the first way to enhance the efficiency of the heat sink is to increase the distance between the heat source and the heat sink. For this reason, in this design, a number of TE modules are attached together in a single stack and this has been used to increase this distance. To determine the capability, five different TE module configurations have been tested and the resulting output for each configuration is shown in Table III. The temperature gradient between the heat source and heat sink is divided over each TE module. If too many TE modules are stacked, the temperature difference between each module is too small, and this small temperature gradient cannot generate enough electrical energy to overcome the energy consumed by the module. This is why the five-layer construction generates less power than the four-layer one. From the experimental results the most efficient stacks is when four TE modules are attached together. Thus, a four layer design is employed in this work.

TABLE III. FIVE DIFFERENT CONFIGURATIONS OF THE TE GENERATOR (RADIATOR TEMPERATURE 323K AND AIR TEMPERATURE 294K)

| Number of modules | Voltage (V) | Current (mA) | Power (mW) |
|---|---|---|---|
| *1* | *0.287* | *97* | *27.839* |
| *2* | *0.361* | *82.3* | *29.7103* |
| *3* | *0.482* | *78* | *37.596* |
| *4* | *0.547* | *72* | *39.384* |
| *5* | *0.586* | *`58* | *33.988* |

Empirically, the temperature of the air surrounding the radiator is not constant over the whole radiator surface area and varies at different position on the surface. If the lowest air temperature position can be found and the TE generator located there, the efficiency of the whole system can be significantly improved. The temperature distributions of the air surrounding the radiator have been tested and results show in Figure 5. From the figure, the lowest air temperature position is at the bottom of the radiator, which is considered as the best position to place the TE generator.

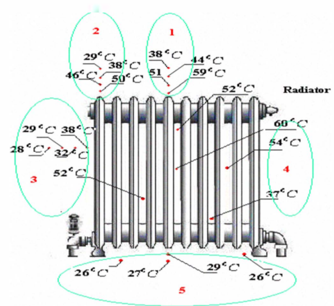


Figure 5. Temperature distribution of the radiator

To proof the concept, the four layers TE generator with the heat sink was placed at five different positions, circled in Figure 5, and tested in the same environment. The comparison result is shown in Table IV and shows that the bottom position can harvest almost twice as much power as the top one.

TABLE IV. FIVE DIFFERENT POSITIONS TO LOCATE TE GENERATOR (RADIATOR TEMPERATURE 323K AND AIR TEMPERATURE 294K)

| Positions | Voltage (V) | Current (mA) | Power (mW) |
|---|---|---|---|
| *1* | *0.475* | *65* | *30.875* |
| *2* | *0.547* | *70* | *38.29* |
| *3* | *0.503* | *68* | *34.204* |
| *4* | *0.487* | *67* | *32.629* |
| *5* | *0.715* | *89* | *63.635* |

Based on the same principle, if the heat from the radiator can be isolated from the air surrounding the heat sink, a larger thermal flow can pass through the modules. Some pieces of sponge or cotton material can be used to efficiently block heat flowing from a hot place to a cold place. Consequently some pieces of sponge was employed to surround the TE modules on the hot side heat exchanger to block heat from radiator. The setup is illustrated in Figure 6.

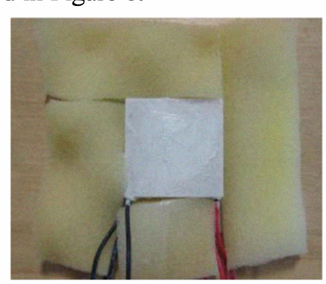

Figure 6. Hot Side heat exchanger with sponges

In order to evaluate the improved efficiency, a hot side heat exchanger without sponge was compared with this design and the result depicts in Table V. From these results, the thermal conversion efficiency of the TE generator was increased by 50% or more by placing some pieces of sponges on the hot side heat exchanger to block the heat.

TABLE V. HARVESTED POWER FOR DIFFERENT HOT SIDE HEAT EXCHANGERS

| Radiator 323K & Air 294K | Voltage (V) | Current (mA) | Power (mW) |
|---|---|---|---|
| *Heat exchanger without sponge* | *0.547* | *72* | *41.328* |
| *Heat exchanger with sponger* | *0.835* | *114* | *95.19* |

### B. DC-DC Converter Subsystem

Comparing the power generated with the power required, the output power of the TE generator is insufficient to directly power the target system. Hence an energy harvesting interface circuit with high power transfer efficiency needs to be developed to change the input power conditions into a suitable form for the target system. The DC-DC converter subsystem is designed to boost the low input voltage from the thermal energy harvesting subsystem, into a higher output voltage to power the ZigBee node and to store the available energy in a storage element. Another additional function of the DC-DC converter is that can isolate reverse current flow from the reservoirs to the TE module.

Nowadays, the start-up voltages of DC-DC converters have been scaled down more and more due to semiconductor technology development. Nevertheless there is still a gap between the output of the thermal energy harvesting system and the minimum required input voltage of a state-of-the-art DC-DC converter. Normally, almost all the step-up converters require input voltage of at least 0.7V to start regulating, whilst the harvesting energy from the radiator is usually less then this threshold. Meeting this higher input voltage requires an additional process between the TE generator and the DC-DC converter. Conventional charge pumps are considered as an ideal component to increase voltage in a circuit. The S-882Z charge pump IC from SEIKO [19] can work as start-up circuit to deliver the required voltages for a boost converter. It is capable of stepping-up the input voltage from as extremely low as 0.3V and outputs a boosted voltage of around 2.2V, sufficient to start-up a booster converter. Moreover, a built-in shutdown function can achieve significant power saving when the output voltage of the connected step up DC-DC converter rises above a threshold voltage. A schematic diagram of the DC-DC converter subsystem is shown in Figure 7. It consists of an S-882Z charge pump, which has 2.5V discharge voltage, in conjunction with a Max757 step-up DC-DC converter [20]. The charge pump starts to work when the input voltage is as low as 250mV. Once the output capacitor CPOUT of the charge pump has reached 2.5V, an internal transistor turns on and a 2.5V charge is delivered as an input source to the MAX757 converter. Then the booster converter starts regulating and its output voltage rises. As soon as the output voltage rises more than 0.7V, the booster converter supplies its own triggering power by feeding the output voltage to the input. Once the booster converter drives itself, the charge pump is short-circuited by the inductor, L1, of the step-up converter. This means the charge pump works only as a start-up circuit and the power consumption of the charge pump need not be considered in the design. From [10], a trade-off must be made when determining the value of the charge-pump capacitor, CPOUT. In order to provide the necessary start-up power for the booster converter, a high value capacitance is required, but this extends the start-up time. In order to reduce the start-up capacitor's to the value lowest at which it is still functional, two 50 uF tantalum capacitors have been employed in parallel in this design. As the voltage of the thermal energy harvesting is very restricted and the generated current is quite high, a high value inductor may be used by the booster converter. It has the capability to reduce the minimal start-up voltage and to provide high efficiency. Thus a high value inductor, 220uh, was used in this design.

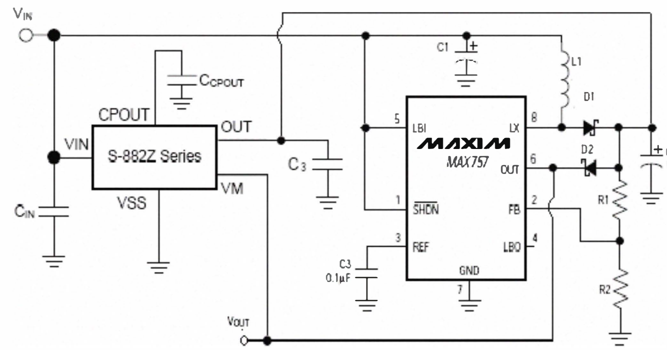


Figure 7. Schemetic diagram of DC-DC converter subsystem

### C. Power Management Subsystem

The main task for the power management unit is to distribute the power to each part of the system and store the available energy in storage elements. In this paper the same design, power management unit developed in [12] has been adopted, but an integrated power management algorithm has been developed. The power management subsystem consists of two storage buffers and control & charge circuit.

There are two reasons for the use of the multiple storage buffers design in the thermal energy harvesting system. Due to the energy harvesting system's behavior, in which the generating voltage would vary over time, it is hard to power the target system directly. Hence, an energy storage element is used to accumulate the available energy delivered by the DC-DC converter subsystem. Furthermore, the energy storage element can work as an energy buffer that can prevent excessive power bursts when the system starts up. Therefore, a high-density energy storage element such as a rechargeable battery must be employed to accumulate and hold the available energy over a long period of time. However, a rechargeable battery has a limited number of recharge cycles and a limited lifetime, which is a critical factor in deciding the lifetime of the whole system. Since the purpose of this research is to prolong the system's lifetime as much as possible, and as the target system must be directly powered by the thermal energy harvesting unit most of the time, the two buffers design, used in [12], has been adopted for this design. Two 2.3V 10F supercapacitors are employed as the primary buffer that can be directly charged by the thermal energy harvesting unit, and which power the target system when enough energy is available. Once sufficient power is available on the primary buffer, it charges the secondary buffer and powers the target system simultaneously. The secondary buffer is used when the energy at the primary buffer is insufficient to power the target system. Two Ni-Cd rechargeable batteries were used as the secondary buffer.

The control & charge circuit is used to optimize the harvested power for the whole system. By comparing the terminal voltage of the primary buffer and using a configured 3.4V threshold voltage, the control & charge circuit determines whether the primary buffer or the secondary buffer should power the target system. In order to enable the charging of the secondary buffer when sufficient energy is available from the primary buffer, another window comparator is used to compare the voltage of the primary buffer and the 4.0V charging threshold voltage. Furthermore, in order to enhance the lifetime of the rechargeable batteries as much as possible, overcharge and undercharge protection is required. To simplify the hardware design, this work can be achieved by loading an overcharge and undercharge algorithm into the ZigBee chip. Moreover, the analogy circuit of the harvesting system such as the comparators and DC-DC converter consume energy when they are working. If the harvesting system can be switched off when there is a little or no thermal gradient between the radiator and heat sink, the energy consumption of the whole system can be significantly reduced. A dynamic power management algorithm is design to turn off the harvesting system when there is insufficient energy in the environment. The algorithm to achieve this was also loaded into the ZigBee chip. An integrated algorithm for the thermal energy harvesting system is shown in Table VI that uses simple if-else statements.

TABLE VI. DRIVER FOR THERMAL ENERGY HARVESTING SYSTEM

| | **Driver** |
|---|---|
| *1* | ***If Battery Voltage >2.9V*** <br> ***Charge Battery=FALSE*** |
| *2* | ***If Battery Voltage<2.1V*** <br> ***Low Battery Warning*** |
| *3* | ***If Harvest Energy Voltage <0.2V*** <br> ***Switch off the harvest system= TRUE*** <br> ***Charge Battery=FALSE*** |

Then the description of the complete circuit for the DC-DC converter and the power management subsystems is completed and a picture of the PCB prototype is shown in Figure 8.

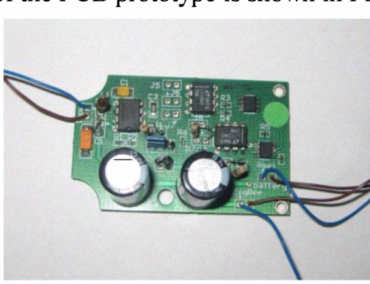

Figure 8. The PCB prototype of DC-DC converter and Power Management Subsystems

## III. EVALUATIONS

A prototype of the thermal energy harvesting system has been developed and tested experimentally to identify its ability to capture thermal energy and convert it into electrical power. The overhead caused by the thermal energy harvesting system's analog circuitry has been tested to identify the system efficiency and the use of the thermal energy harvesting system to power ZBARV system has been evaluated.

### *A. Experimental Setup*

Figure 9 shows the experimental setup which was used to evaluate the proposed platform. A 1.5KW electrical radiator, which can vary the heat output by adjusting an on board regulator, was employed to emulate the normal radiator in the laboratory. In order to harvest enough thermal gradient energy from the radiator, two heat sinks and eight TE modules were used to fabricate the thermal energy harvester. In this design, four of eight modules were attached together in a stack by using high efficient thermal grease and then located between the heat sink and a thin aluminum plate. Additionally, some pieces of sponges were used to isolate heat from the radiator. For easy installing, the thermal energy harvesting subsystem was fixed on the top of the radiator. In order to monitor the temperature of the hot and cold sides of the TE Modules, an Omega CO-1 thermocouple [21] was used.

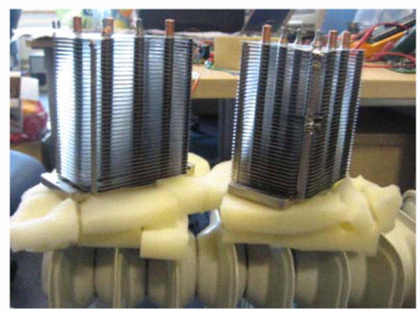

Figure 9. Experimental Setup for Thermal Energy havesting system

### *B. Thermal Harvesting Efficiency*

In order to evaluate the thermal energy harvesting efficiency of the prototype, the generator was tested in the laboratory at different temperatures with a room temperature of $21\,^{o}C$. The results are shown in Figure 10 and indicate that the maximum harvested power is around 150mW when the hot side temperate is $55\,^{o}C$.

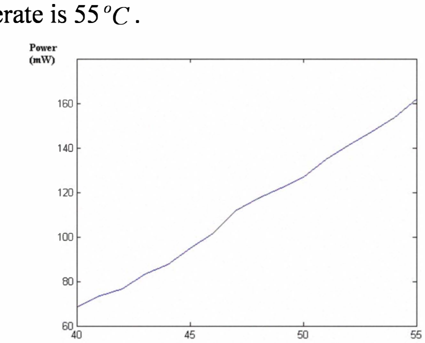


Figure 10. Output voltage of the TE generator as a function of the hot side temperatures

## C. DC-DC Converter Efficiency

A practical implementation of the DC-DC converter system was tested with different input power to evaluate efficiency and the results obtained are show in Table VII. The output voltage of the booster converter was set to a constant voltage of 5V. The experimental results show that the efficiency of the booster DC-DC converter is related to input power and the converter system works even when the input voltage is as low as 0.32V and the average efficiency of the system is around 30%.

TABLE VII. MEASUREMENT RESULTS OF THE DC-DC CONVERTER

| Input Voltage (V) | Input Current (mA) | Output Current (mA) | Efficiency |
|---|---|---|---|
| *0.32* | *59* | *1.1* | *29%* |
| *0.43* | *62* | *2.0* | *37.5%* |
| *0.47* | *65* | *2.4* | *39%* |
| *0.51* | *70* | *3.5* | *46%* |
| *0.63* | *89* | *5.5* | *49%* |

Next the thermal energy harvesting subsystem was integrated with the DC-DC converter subsystem to test the overall efficiency. The power output of the integrated system was used to charge two supercapacitors from 2.5V to 4V. The charging time provides a simple way to interpret efficiency and the measured times are shown in Table VIII. The experimental results showed that the most efficient charging occurs when the thermal energy harvesting subsystem generated the maximum power.

TABLE VIII. CHARGING TIME FOR THE THERMAL ENERGY HARVESTING SYSTEM

| Harvested Voltage (V) | Charging Time (S) |
|---|---|
| *1.485* | *846* |
| *1.372* | *987* |
| *1.04* | *1196* |
| *0.91* | *1245* |
| *0.85* | *1489* |
| *0.74* | *1839* |
| *0.65* | *2385* |
| *0.53* | *3130* |
| *0.45* | *4109* |

## D. Power Management Subsystem Test

The Power management subsystem with ZBARV was verified by simply connecting the primary buffer (supercapacitor) to a DC power supplier, PSU 130. Initially, the ZigBee node was powered by the secondary buffer (two rechargeable batteries) while the DC power supplier charged the primary buffer. When the first threshold of 3.4V was met, the power management unit triggers the P-MOSFET to switch from the rechargeable batteries to the supercapacitors. Then the whole system was then powered by the supercapacitors. While the input power was increasing, the power accumulated on the supercapacitors was rising. Once the capacitor's voltage reaches 4.0V, the comparator switches on the adjustable current limit switch and transfers the capacitor's energy to the rechargeable batteries. Then the DC power supplier is turned off and the voltage of the capacitors drops. When the voltage drops less then 4.0V, the capacitors stop charging the rechargeable batteries. Furthermore, once the voltage is less then 3.4V, the rechargeable batteries again start to power the ZigBee chip. These phenomena correctly fit the design principle, which was mentioned in the power management subsystem. For the dynamic power management test, the power management algorithm was loaded into the ZigBee chip. The experimental results showed that the thermal energy harvesting system could be switched off when there was insufficient thermal energy in the environment. For the overcharge and undercharge protection test, the software was again loaded into the ZigBee chip. In order to simplify the testing, a 22F supercapacitor was used to replace the batteries. The experimental results showed that the ZigBee chip monitors the capacitor's voltage correctly and the control signal changed as required.

## E. Analog Circuit Overhead

In order to measure the current consumption of the whole thermal energy harvesting analog circuit, the PCB board without the TE energy harvesting subsystem has been tested. When a 3V battery is used to power the circuit, the current consumed by the analog circuit is around 700uA. This shows the importance of switching off the circuit when there is insufficient power produced by the TE generator.

## F. Integrated System Test

To evaluate the whole system, the three subsystems were integrated into one and tested with a ZBARV in an actually environment for four days. The test setup is shown in Figure 11. The terminal voltage of the rechargeable batteries was recorded each day. The experimental results showed that the system worked autonomously as expected without any additional power requirements. When the radiator was turned on, the thermal energy harvesting system harvested thermal gradient energy from the radiator and uses this energy to charge the primary buffer. When the ZBARV was in sleep mode, it uses power from the primary buffer. The primary buffer charged the secondary buffer when it had sufficient power. When the ZBARV was working, the system automatically switched to using the batteries to power the whole system. Once the radiator was switched off, the ZigBee chip sent an OFF signal to the control and charge circuit to switch off the thermal energy harvesting system to save energy.

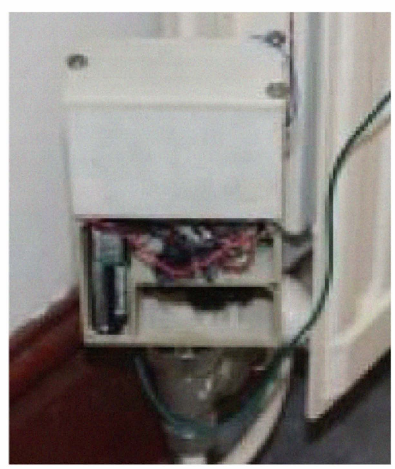

Figure 11. The thermal energy harvesting system with ZigBee Based Automatic Radiator

## IV. CONCLUSION

Energy is a limited resource in wireless electronics and power supplies and making sufficient energy available is perhaps the most challenging technological hurdle to be overcome in the widespread development of WSNs. In fact, the goal of many wireless sensor nodes is to develop a completely self-powered electronic module that can be placed in a remote location without any need to replace the power supply. In this research, a highly efficient thermal energy harvesting system with the thermal energy harvesting subsystem, DC-DC converter subsystem and power management subsystem has been developed to generate electrical energy from ambient thermal gradients. The evaluation of the thermal energy harvesting system showed the applicability of the proposed system. A case study was presented for extending a ZBARV's lifespan. The experimentation highlighted that a ZigBee based radiator valve's lifetime could be greatly improved by using the thermal energy harvesting technology. Base on the theoretic calculation, the lifetime of the whole ZigBee system could be extended for more than 8 years. This work also presented two more contributions. Firstly, some design considerations for low temperature thermal energy harvesting systems and some efficient ways to maintain the temperature difference between the two sides of the TE module were proposed. Secondly an ultra low dropout voltage step up DC-DC converter and high efficient power management system was developed. There are some limitations to this design. The main limitation is that the efficiency of the whole harvesting system is not high enough for low temperature applications. Secondly, the conversion coefficient of the DC-DC converter is quite low. Furthermore, the size of the thermal energy harvesting subsystem is quite large because of the size of the heat sinks. In future work we will focus on how to enhance the efficiency and improve the system design. Normally, there are three possible ways that could be considered in order to improve the system. Finding a more efficient type of TE module and designing a more efficient heat sink is the first considerations for any future work. Designing a more efficient low input voltage DC-DC converter system is another possible way to improve the system efficiency. Finally, a maximum power point tracking system, promised a significantly improvement in the efficiency of the whole system and will be studied in the future.


## ACKNOWLEDGMENT *(HEADING 5)*

This work was supported by Carbon Connections. Thanks to the contributions made by Fang Yao in the Network Communication and Control Systems Research Division in the Department of Computer Science, Loughborough University.


## REFERENCES


[1] A.J.Minnich, M.S.Dresselhaus, Z.F.Ren and G.Chen, Bulk nanostructured thermoelectric materials: current research and future prospects, Energy And Environmental Science, DOI: 10.1039/b822664b,2009.

[2] Jyrki Tervo, Antti Manninen, Risto Ilola and Hannu Hanninen, State-of-the-art of thermoelectric materials processing,VTT Technical Research Center of Finland, Vuorimiehentie, ISBN 978-951-38-7184-0. 2009.

[3] Etienne Schwyter, Wulf Glatz, Lukas DUrrer, Christofer Hierold, Flexible Micro Thermoelectric Generator based on Electroplated Bi2TE3,DPIP of MEMS & MOEMS ISBN: 978-2-35500-006-5,2008.

[4] H. Bottner, "Thermoelectric Micro Devices: Current State, Recent Developments and Future Aspects for Technological Progress and Applications," Proc. of 21st International Conference on Thermoelectric, pp. 511–518, 2003.

[5] M. Kishi, H. Nemoto, T.Hamao,M.Yamamoto, S.Sudou, M.Mandai and S. Yamamoto, Micro-Thermoelectric Modules and Their Application to Wristwatches as an Energy Source, SEIKO Instruments, 18th International Conference on Thermoelectrics, 0-7803-5451-6,1999.

[6] Matthew Kocoloski, Carl Eger, Robin Mccarty, Kevin Hallinan, Kelly Kissock, "Industrial Solid-State Energy Harvesting: Mechanisms and Examples", ACEEE summer study on Energy Efficiency in Industry, P 55-68, 2007.

[7] Jensak Eakburanawat, Itsda Noonyaroonate, " Development of a thermoelectric battery-charger with microcontroller-based maximum power point tracking technique", Applied Energy, Volume 83, Issue 7, Pages 687-704, 2005.

[8] Dan Mastbergen, Bryan Willson, and Sachin Joshi, 2005, Producing Light from stoves using a thermoelectric generator, Engines and Energy conversion laboratory, Department of Mechanical Engineering, Colorado state University, http://www.bioenergylists.org/stovesdoc/ethos/mastbergen/Mastbergen_ETHOS_2005.pdf

[9] Henry A. Sodano, Garnett E. Simmers, Remi Dereux and Daniel J.Inman, Recharging batteries using energy harvested from thermal gradients, Journal of Intelligent material systems and structures, Vol. 18, PP3-10, 2006.

[10] Loreto Mateu, Cosmin Codrea, Nestor Lucas, Markus Pllak and Peter Spies, Energy harvesting for Wireless communication systems using thermogenerators, http://www.iis.faunhofer.de/fhg/Images/mateu_et_al_fv_dcis2006_tcm97-73301.pdf

[11] John M.Damaschke, Design of a low input voltage converter for thermoelectric generator, IEEE Transactions on industry applications, VOL. 33, NO.5,1997.

[12] Xin Lu and Shuang-Hua Yang, Solar energy harvesting for ZigBee Electronics, Sustainability in energy and buildings, DOI 10.1007/978-3-642-03454-1, P19-27, 2009.

[13] Khusvinder Gill, Shuang-Hua Yang, Fang Yao and Xin Lu, A ZigBee-Based Home Automation System, IEEE Transactions on Consumer Electronics, Vol.55, No2, May 2009.

[14] Jennic Ltd., JN5139-xxx-Myy Module, http://www.jennic.com/files/product_briefs/JN5139-xxx-Myy-PB_v1.2.pdf

[15] G. Ben Humida, A.L.Ekuakille, A Kachouri, H.Ghariani, and A. Trotta, , Extracting electric power from human body for supplying neural recording system, International Journal on Smart Sensing and intelligent system, Vol. 2. NO.2. .

[16] Y.Meydbray, R. Singh, and Ali Shakouri, Thermoelectric module construction for low temperature gradient power generation, 2005 International Conference on THermoelectrics, pp 348-351.

[17] Taicang TE cooler co., Ltd. TEC1-12709, http://www.taileng.com

[18] Auras's 3 U heat sink, http://auras.com.tw/ppdtview.asp?nid=230

[19] Seiko Instrumetns, S-882Z Ultra-Low Voltage operation charge pump, http://www.Eet-china.com/ARTIVLES/2006MAY/PDF/S882Z_E.pdf

[20] Maxim 3.3V/5V DC-DC Converter, http://datasheets.maxim-ic.com/en/ds/MAX756-MAX757.pdf

[21] Omega CO-1 thermocouples, http://www.Imega.co.uk/Temperature/pdf/CO-k.pdf