ENVIRONMENTAL THERMAL ENERGY SCAVENGING POWERED WIRELESS SENSOR NETWORK FOR BUILDING MONITORING

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ABSTRACT: In recent years there has been increasing interest in innovative design and construction of sustainable high-performance buildings. Among the innovative techniques proposed to increase building performance is to dynamically sense, control and manage the ambient building environment, such as temperature, humidity, air quality, artificial lighting, etc. through the installation of a distributed wireless sensor network (WSN). It has been reported that such an intelligent building monitor and control system can result in an approximately 20% savings in energy usage, a substantial step toward the realization of smart building management. In conventional WSNs, battery power is used to energize these micro-scale sensors. The small space permitted for battery integration in these miniaturized systems is a limiting factor. The small battery will be quickly depleted requiring frequent battery replacement or the WSN system will cease operation. Frequent battery replacement is impractical due to the tremendous number of sensor nodes embedded in a typical WSN system. This key design challenge in WSN based building monitoring and control must be overcome in order to significantly prolong the life of the overall system operation. In this paper, the authors investigate the construction of a novel WSN system for intelligent building environment monitoring powered through the use of micro-scale thermoelectric generators (TEG). In the TEG, the ambient thermal gradient between two surfaces of the device is converted into electrical energy. To verify the feasibility of the proposed idea, an experiment was conducted and the results demonstrated the concept of harvesting ambient thermal energy to power wireless sensors.

***Keywords**: Energy Harvesting, Thermoelectric Generator, Wireless Sensor Network*

1. INTRODUCTION

According to the U.S. Green Building Council, buildings account for 39% of CO_2 emission and consume 70% of the electricity energy in the United States [1]. For the past decade, innovations in the design and construction of sustainable green buildings have been receiving growing attention. Utilizing renewable energy (e.g., solar irradiance) as alternative power supplies has been applied in a number of state-of-the-art smart buildings. In addition, researchers have revealed that sensor technology has a high potential to contribute to the reduction of CO_2 emissions and energy dissipation. A distributed sensor network can collect the building environment parameters, such as artificial lighting, temperature, air quality, humidity and so on. Then, these parameters are transmitted to a central control computer, which runs a certain algorithm or software to dynamically optimize the HVAC system operation and provide efficient heating, cooling, lighting, and ventilating [2]. A small operation adjustment to HVAC systems can significantly reduce energy usage and loss. This attractive and practical option can extensively contribute to energy savings and environmental benefits. It has been reported that such an intelligent building monitoring and control system can result in an approximately 20% savings in energy usage, a substantial step toward the realization of smart building automation and management [3].

In the past, manual measurement and recording by building management personnel was the primary approach utilized to optimize the operation of HVAC systems. However, due to the limited data collection capability of facility management personnel, it is very difficult to sample sufficient data for intelligent monitoring and control for real-time optimization. Moreover, the associated overhead cost of expensive labor required for manual data sampling is another concern. Fortunately the rapid advances of sensor manufacturing technology have allowed the size of a sensor node to shrink into millimeter or centimeter scale. As a consequence, installing tens or hundreds of tiny sensor nodes inside a building does not cause much inconvenience to building users or residents. Typical sensor nodes have been able to integrate wireless communication capability to form a wireless sensor network (WSN). Compared to conventional cable-connected wired senor networks, a wireless sensor network has obvious advantages in terms of cable/wire routing, ease and flexibility of installation, and low cost implementation. Therefore, use of a WSN can be viewed as a cost-effective enabling platform for intelligent environment monitoring and HVAC operational adjustment for future energy-efficient green buildings.

To date, there have been several WSN systems presented in literature for intelligent building environment sensing and monitoring [4-7]. However, in these WSN systems, battery power is used to energize the micro-scale sensors. The operation of each sensor node is heavily dependent on the remaining energy status of its associated battery. The small space permitted for battery integration is a limiting factor in these miniaturized systems. Even when a very high energy density battery is chosen, the battery will be drained within several months resulting in sensor network shutdown. Frequent battery replacement in distributed sensor nodes causes high replacement labor costs resulting in a primary design challenge.

To deal with this severe problem and challenge, researchers have proposed a series of environmental energy harvesting techniques. Environmental energy harvesting is a physical process by which the electrical energy is converted and extracted from our immediate surroundings. Examples of ambient energy sources include light, heat, mechanical vibration, electromagnetic wave, etc. Harvesting energy from the surrounding environment is of growing interest to alleviate the power supply challenge in WSN systems [8-10]. In [9], the researchers showed the estimated power levels possible through environmental energy harvesting techniques. They concluded that the harvested power is sufficient to sustain a typical wireless sensor operation. In [10], the system design perspectives of a small scale energy harvesting system were reviewed and discussed elaborately.

The idea of scavenging environmental energy to sustain low power electronics is not new. Wireless sensor nodes that harvest outdoor sunlight energy, such as the Helimote sensor module developed by UCLA [9], have been presented in literature. In [11], the use of environmental thermal gradients to charge batteries was investigated. In [12], the authors demonstrated the feasibility of operating a WSN system in indoor weak light conditions. However, light energy harvesting has very low efficiency and may be impossible when the position of sensor node is far away from the light source, such as when some senor nodes are required inside a wall or in dark corners of a building. In these scenarios of dim lighting, light energy harvesting cannot support the normal operation of WSN systems. Therefore, it is necessary to investigate and study other energy harvesting mechanisms to effectively power WSN systems.

The focus of this paper is to explore a new wireless sensor network that uses an environmental temperature gradient (i.e., heat flux) as an alternative power source to mitigate the previously described weakness of WSN systems. As will be shown later in the paper, a thermoelectric generator (TEG) is used as an energy harvesting device, converting the thermal gradient between two surfaces of the device into electrical energy. To verify the feasibility and evaluate the performance of the proposed idea, an experiment was conducted to evaluate thermal energy scavenging powered WSNs. The results demonstrate the feasibility of harvesting ambient thermal energy to power wireless sensors.

2. THERMAL ENERGY HARVESTING

Temperature gradients commonly occur in various household or industrial settings. It is estimated that temperature gradients inherent in the environment can provide power for sustainable operation of a sensor node [8]. A micro scale thermoelectric generator (TEG) is a type of scalable, reliable solid-state device. Fig. 1 illustrates its internal structure and operational mechanism. Micro-scale TEGs typically consist of multiple p-type and n-type thermoelectric couple legs, which can output electrical energy by employing the temperature gradient between the high temperature surface and low temperature surface. These thermocouples are usually connected thermally in parallel and electrically in series to effectively make use of the limited surface area. When there is a thermal gradient through a TEG device, as illustrated in Fig. 1, charged carriers (i.e., electrons and holes) move from the hot surface towards the cool surface, thus a flowing current and terminal voltage are generated.

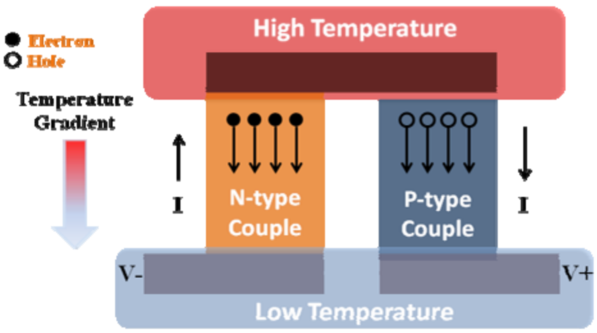

Fig. 1 TEG Device Structure and Operational Mechanism

Micropelt MPG-D751 [13] is a good example of a small scale TEG device. Its open circuit voltage is proportional to the number of thermoelectric couples and the temperature difference. According to the measurement data provided by the manufacturer, its dimension is only a few millimeters. The product manual of MPG-D751 indicates that a temperature difference of 3.5^{o}C is able to generate 200μW of electrical power, which is sufficient to broadcast data once per second in a wireless sensor node [13].

3. TEG POWERED WIRELESS SENSOR NODE

The wireless sensor node employed in this paper is a commercial product from Micropelt Inc [13]. There is no battery used as the power supply, and a micro-scale TEG device is used as the energy harvesting device, as shown in Fig. 2. The thermal gradient across its two surfaces is converted into electrical energy to power the operation of the sensor node. Two embedded temperature sensors and a RF signal transceiver (CC2500, Texas Instruments), enable wireless transmission of the sensed environmental temperature values between a central control computer and the wireless sensor node, as shown in Fig. 3.

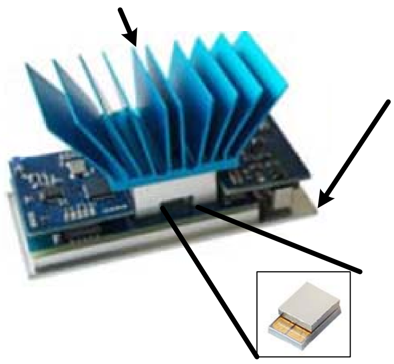

Fig. 2 Micro-Scale TEG Powered Wireless Sensor Node

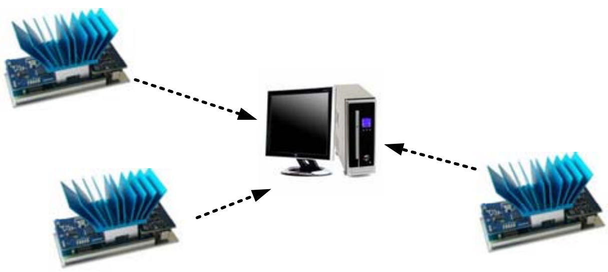

Fig. 3 WSN Architecture for Building Monitoring System

4. EXPERIMENTAL RESULTS

To verify the proposed idea of harvesting thermal gradients from the environment to power WSN systems, an experiment was set up on the 4th floor of Knoy Hall at Purdue University. As shown in Fig. 4, a wireless sensor node was installed on the top of a floor mounted vertical fan coil unit, which is often utilized inside buildings to provide cooling in summer and heating in winter. When the fan coil unit works, a thermal gradient exists between its top coils and the ambient air. By adjusting the operational status of the fan coil unit, a time-varying thermal gradient was generated. The experiment lasted for thirty minutes and the total number of sensed data points was 1050. Fig. 5 plots how the sensor surface temperatures varied during this experiment. Fig. 6 plots the measured temperature differences between the two surfaces. From Fig. 6, it can be observed that the temperature difference had a variation rage from 3.7^{o}C to 8.6^{o}C in this experiment.

Fig. 4 Experimental Setup of a TEG Powered WSN

During the 30 minute experimental period, the central control computer was able to successfully receive the transmitted data from the sensor node. In this experiment, the maximum reliable communication distance from a sensor node to the central control computer was measured as 15 meters. The presence of surrounding concrete walls or wood doors did not severely diminish the signal strength of the wireless data transmission.

Because the ambient thermal gradient may be very unstable in practice, a self-starting feature is crucial for this battery-less WSN system. When there is no heat flux or the temperature difference is too low to be harvested by the TEG device, the WSN system will run out of its remaining energy and stop working. If the system did not have the self-starting capability, later when the thermal gradient became high enough for harvesting, the system could not restart. In this experiment, the sensor node was temporarily moved to a place where little thermal gradient existed. The central control computer did not receive any transmitted signal from the senor node during this period. Later, when the sensor node was moved back to the fan coil unit, the central control computer was reconnected with the sensor node after a delay of a few minutes. This phenomenon validated the self-starting capability of this system. As a result, it can operate in a long-lived, maintenance-free manner, saving the labor and material cost of battery replacement.

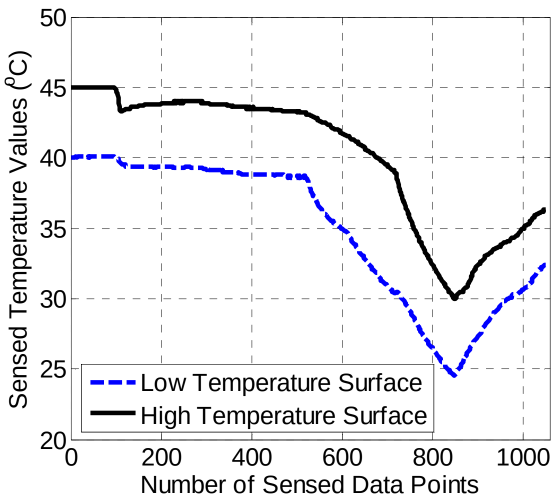

Fig. 5 Measured Sensor Surface Temperature Variation

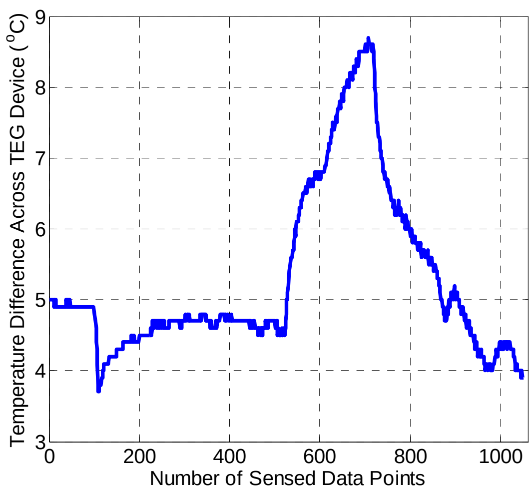

Fig. 6 Measured Thermal Gradients across the Sensor

Based on this experiment, the authors predict and propose that this thermal gradient powered WSN can also be used as a fire alarm system inside buildings. Users may place these tiny wireless sensor nodes in places that are prone to over-heat or catch fire. Thus, when the temperature of these sensitive places increase to a threshold value, the sensor node would be powered up and would transmit a signal to the central control computer. The benefits of this system include reduced maintenance (i.e., battery replacement) complexity, rapid warning, and reduced labor cost.

5. CONCLUSIONS

Distributed use of a wireless sensor network (WSN) is a promising solution to optimizing control and management systems in support of the efficient operation of a building's HVAC system. However, retrofit battery powered WSN systems suffer from the difficulty of frequent battery replacement and high labor cost, which impedes its practical use for building monitoring, control and management. In this paper, the authors investigated a temperature difference powered WSN system that harvests the environmental thermal gradients as the power supply. To verify the potential of the proposed idea, an experiment at Purdue University was conducted. The results validate the concept of harvesting ambient thermal energy through a small TEG device.

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