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# Power Consumption Performance Analysis of a Wireless Sensor Node Operates with Thermoelectric Harvester

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**Abstract:** Since, the demand for an autonomous systems such as Wireless Sensor Network (WSN) nodes or Internet of Thing (IoT) devices is growing these days and due to the fact the periodic maintenance and battery replacement for such systems may not be an economical solution, therefore battery substitution with an energy harvesting system is crucial. The direct output current of the Thermo Electric Harvester (TEH) has made it a popular potential of electrical energy source to substitute battery, however the energy that's generated by TEH needs to match the minimum electrical power requires to operate the electronic system. The focus of this research paper is to investigate the power consumption of a wireless sensor node which is powered by TEH. The wireless node in this project contains a MEGA328P Micro Controller Unit (MCU), a wireless transceiver nRF24L01, DHT22 sensor and a thermal energy harvester with a power conditioning circuit. The system is equipped with an energy aware algorithm to reduce the power consumption. This algorithm lets the node sleep for 10 sec and then wake it up for a few millisec to read and send a data. The experimental results show that the system required 46 mW in sleep mode while it consumes about 53.5 mW during active mode. The operational performance of the system is evaluated using 7.4 V rechargeable Lipo battery and compared with TEH in term of operational longevity. The results show that the Lipo battery able to operate the system continuously for 33 h whereas the TEH has successfully kept the system running as long as there is a heat source with a gradient of 40°C.

**Key words:** Thermal energy harvesting, power conditioning circuit, wireless sensor network internet of things, source

## INTRODUCTION

Wireless Sensor Nsetworks (WSNs) alongside with Internet of Things (IoT) technology has been successfully utilized in abounding commercial fields in the most recent decade (Yick *et al*., 2008; Begum and Dixit, 2016). The increase in the demand for such autonomous systems and the more attention from users and researchers is due to its colossal application esteem. Typically, WSN node consists of an MCU, wireless module, sensors and power supply on a small board. Batteries are the usual power supply for most of the sensor nodes with very limited performance. Commonly the performance and the power of the WSN differs with the intended application and hence, the power consumption. Where industrial WSN required higher sampling rates and faster data transmission compared to general purpose WSN which will undoubtedly require more power (Hou and Bergmann, 2012; Hou and Tan, 2016). Furthermore, frequent battery replacements and node servicing is an inconvenient and uneconomical solution. Consequentially, batteries have become a crucial issue that hinders WSN performance. As a rule of thumb, a node within the WSN required a power supply of milliwatts magnitude to survive. Although, numerous number of researchers and developers around the globe are working on reducing the node's power consumption to prolong the lifetime. Whereby low power node can be achieved by exploiting low power modules for the architecture, large batteries and by utilizing an energy aware software algorithm (Bachmann *et al*., 2012). However, all the previous solutions are still critical regarding the battery's lifetime. Therefore, batteries elimination is a must to guarantee long term wireless node. Now a days and with the development of Energy Harvesting (EH) approach where it can be utilized to capture the wasted energy around us like mechanical impact (Abdal-Kadhim *et al*., 2016a) vibration

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(Abdal-Kadhim *et al*., 2016b), solar (Chien *et al*., 2016) heat (Goh and Kok, 2017), etc. and recover it into a small but useful amount of electrical energy. Due to the latest developments in thermoelectric materials and structures (Attivissimo *et al*., 2014; Bobean and Pavel, 2013). And since, the heat resources are abundantly available in our daily lives where heat can be easily found during the day from the sun, household devices such as kettle and cooking stove and industrial machines such as engines and motors. Therefore, have led to reviving the interest in thermal to electrical energy harvesting which offers a new and attractive substitution to the conventional battery as the main power supply. Therefore in this study, Thermal Energy Harvesting (TEH) is being chosen as the main power supply for the proposed wireless node in this research.

TE harvester has shown promising features such as long life cycle, no moving parts needed, simplicity and high reliability. These days, the interest of thermal energy harvesting growing faster and more investigations is moving into its area where there are some successful industrial applications using TE generators. The Seiko Thermic watch considered the first application ever of thermal energy harvesting to a consumer product (Kishi *et al*., 1999). The wristwatch was driven via a TE module to convert the user's body heat into electrical energy. A 22 μW can be harvested by the TE module with about a 1K temperature gradient between the wrist and the environment at room temperature. Moreover, this harvested energy not only drives the watch but also charge a 4.5 mAh lithium-ion battery. On another context, plentiful of researchers and developers are investigating the potential of utilizing TEH as a wireless node's power supply. Dalola and his colleagues (Dalola *et al*., 2009) have presented a novel TEH module and they succeeded to utilize it in powering up a wireless sensor node for temperature measurement application. Furthermore, a small size TEG is proposed by Bonin *et al*. (2013), this TEG utilized for environmental monitoring applications, the proposed small size TEG was capable of recovering about 10 mW of electrical power whenever there is 10 k of temperature gradient. Other researchers developed a novel ultra-low power management circuit for an autonomous multisensory system for agricultural application where was powered via. thermal energy harvester (Dias *et al*., 2015). They succeeded to harvest about 110 mV/°C and also prolong the system life from 136 h to more than 266 h. Dejan Rozgic and Dejan Markovic presented a thin-film array-based thermoelectric energy harvester fabricated in a 0.83 $cm^2$ footprint along with a power management unit integrated in 65 nm CMOS. Their prototype was targeted for biomedical applications where they achieved 645 μW regulated output power harvested in-vivo from a rat implanted (Rozgic and Markovic, 2015). Zhang and his fellows have moved a step forward by presenting a TEG module to exploit the sun irradiation and the temperature variation of the earth's surface (Zhang *et al*., 2015).

## MATERIALS AND METHODS

**Theory of Seebeck effect and TEH:** The TE harvester employing Seebeck effect which it's discovered in 1821 by Tomas Seebeck (CIT., 2007). This behavior is described as when heating up one end of a thermoelectric material and cooling down the other end will cause the diffusion of the charge carrier from the hot end to the cold end. Resulting an electrical current at the end terminals of the TE element. A typical thermal model of a TEG is illustrated in Fig. 1a. The heat power flows from the heating element $T_h$ throughout the TEG module $T_{TEG}$ and ending up to the adhered heat sink $T_c$, so, the heat sink will play a role of a heat distributor to cool down the unit. Regarding to the electrical model of a TEG can be implemented via. Seebeck voltage $V_S$ (Fig. 1b). Which its content a Seebeck voltage along with an internal resistance $R_{TEG}$ (Freunek *et al*., 2009; Han *et al*., 2010). The TEG module open circuit voltage can be *addressed as:

$$V_s = \int_{Tc}^{Th} (S_B(T)-S_A(T))dT \quad (1)$$

Where:

$S_A$ and $S_B$ = The Seebeck coefficients
$T_h$ and $T_c$ = Representing the temperatures of the two junctions

By assuming that the Seebeck coefficients will not change regarding with the measured temperature range as a result Eq. 1 can be rewritten as:

$$V_s = \alpha\Delta T \quad (2)$$

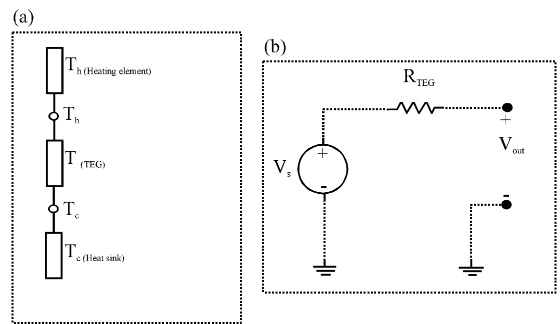


Fig. 1: TEG equivalent circuit; a) thermal model and b) electrical model

where, the Seebeck coefficient α = (S A-S B) and the temperature difference at the TEG surfaces $\Delta T = (T_h - T_c)$. By observing Eq. 2 with assuming that Seebeck coefficients α is constant can comprehend that the recovered Seebeck voltage $V_s$ is directly proportional to the exposed temperature gradient ΔT.

## RESULTS AND DISCUSSION

**Wireless sensor node design and evaluation:** The $WSN_{\_2\_TEH}$ wireless sensor node is designed based on low-power CMOS 8-bit AVR Microcontroller ATmega328P, a humidity and temperature sensor DHT22, and 2.4-2.5 GHz wireless transceiver nRF24L01. Since, $WSN_{\_2\_TEH}$ is targeted to utilize TEH as the main power supply for the system, therefore, a power conditioning circuit based on low-power DC-DC boost converter TPS61041 designed to regulate the system power. In order to cut down the node manufacturing cost, also in low-temperature gradients below 100°C, a TEC Peltier module can be utilized as a TEH as good as a TEG module, add on single TEG unit is 5 times more costly than a TEC unit (Nesarajah and Frey, 2016). Subsequently, it's been chosen to utilize a TEC unit instead of TEG unit to conduct this research.

The proposed power conditioning circuit required as low as 1.5 DC.V to operate and boosts it up to about 5 DC.V. From the previous research (Ali and Kok, 2017) where an increment of 0.5 V was obtained with every stacked Peltier unit. In this study, only two Peltier units from Laird [HT8, 12 Laird UM08] stacked on each other and electrically connected in series were used which is sufficient as the main power source of the system. These two units were able to deliver the required voltage to trigger on the booster circuit at a temperature gradient of ΔT = 40°C. A capacitor of 8200 μF10 V utilized to store the output voltage before feed it to the system. Figure 2 depicts the architecture of the proposed wireless sensor node.

The TPS61041 is being chosen based on the availability, low cost, easy to use and low start up voltage as well. Moreover, the TPS61041 circuit as shown in Fig. 2 above consists of a bunch of off-the-shelf passive components only. Aside from the components appeared in Fig. 2, a Schottky diode (NSR0320MW2T1) used in D1. This Schottky barrier diode is chosen due to the high current capability with low forward voltage dropping. This conditioning circuit was able to deliver DC power of 95 mW at load of 250 Ω. Figure 3 illustrates the power measurement of the conditioning circuit. The 95 mW of electrical power considered more than enough to keep the $WSN_{\_2\_TEH}$ node up and running. The fabrication of the

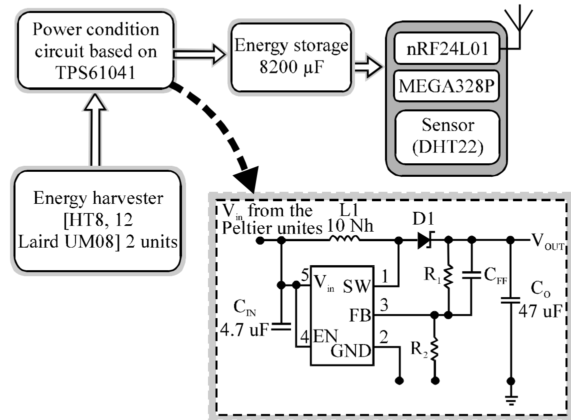


Fig. 2: The architecture of the WSN_2_TEH

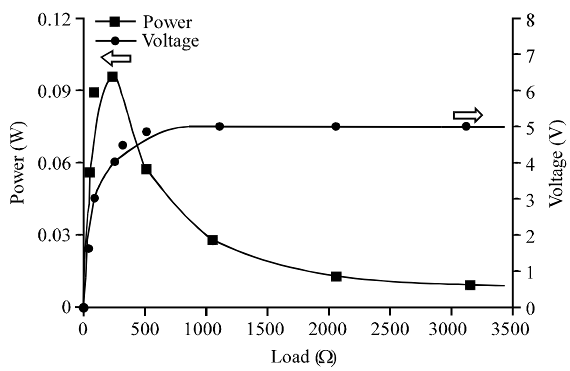


Fig. 3: The power measurement of the conditioning circuit

proposed $WSN_{\_2\_TEH}$ node is presented in Fig. 4. Since, the TEH approach will be the main power source for the proposed $WSN_{\_2\_TEH}$, therefore, an energy aware algorithm developed to handle that and manage the power consumption of this node. This algorithm keeps the node in a sleep mode for some time to give a chance to the power conditioning circuit to store the energy for the next active mode. Figure 5 shows the details of the proposed software algorithm for the $WSN_{\_2\_TEH}$.

Directly after exposing the cascaded peltier elements to a temperature gradient of ΔT = 40°C, the peltiers start to recover about 1.5 DCV. After that, the mentioned power conditioning circuit is taking over in powering up the $WSN_{\_2\_TEH}$ system. And then, according to the algorithm in the Fig. 5 the microcontroller is initializing and reset all the internal registers and the peripherals. The MCU has then been set, so that, the system going into a sleep mode for 10 sec. During this period and due to the fact that the system power consumption is at minimum magnitude at this point, so, the power conditioning circuit has a chance to build up the energy for the next active period. Later on, the MCU will wake up and carry on reading the data from

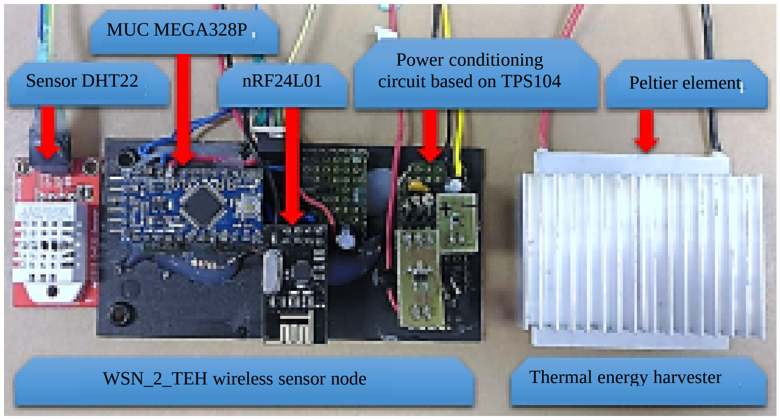


Fig. 4: The fabrication of the WSN_2_TEH Wireless sensor node

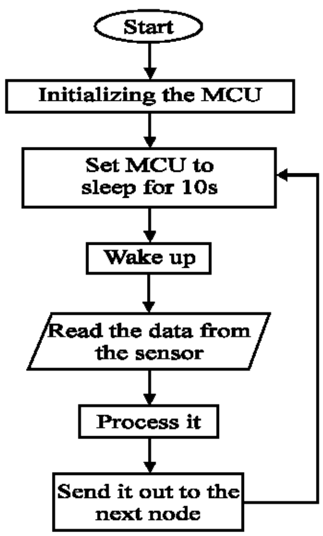


Fig. 5: The proposed software algorithm for the WSN_2_TEH node

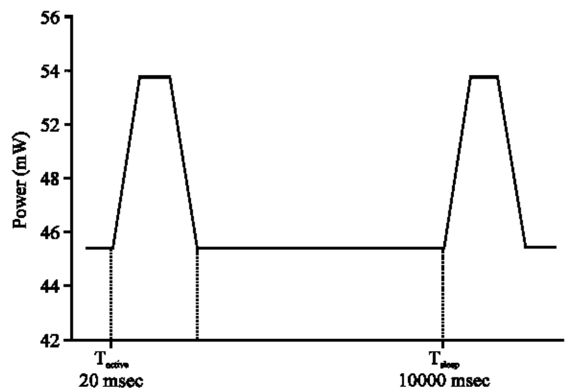


Fig. 6: The WSN_2_TEH wireless sensor node power consumption at different operation modes

the attached sensor. The MCU will broadcasting out the data to the next node directly after processing it through the nRF module. Thenceforth, the MCU will keep on altering between these two modes. Based on the measurements finding, the $WSN_{2\_TEH}$ active mode takes about 20 msec to read the data from the sensor, process it and transmit it out and required about 53.5 mW of power. Whereas, the $WSN_{2\_TEH}$ consumes about 46 mW only during the sleep mode. Figure 6 shows the timing and the power consumption for each mode of $WSN_{2\_TEH}$ system.

**Conventional battery versus teh as wsn node power source:** Furthermore and for the sake of demonstrating the advantages of utilizing THE approach upon a conventional battery as a wireless sensor node power source. The $WSN_{2\_TEH}$ wireless node that is shown in Fig. 4 is powered by a rechargeable lithium polymer battery "7.4 V, 500 mAh capacity" manufactured by KingMax. After that, the battery is supplanted with the TEH approach. The wireless node performance with each of power sources was experimentally recorded. About 33 of continuous working hours only is the maximum time that the battery can supply to the wireless node before it fully drained out and it has no chance to initiate the MCU again "means the battery need to be changed/recharged". Subsequently, the $WSN_{2\_TEH}$ node was completely out of service.

However, by utilizing two cascaded Peltier units as a power source, electrically connected in series and exposed to a 40°C of a temperature gradient, whereby from the previous work (Kadhim and Kok, 2017), 40°C considered an average temperature gradient can be

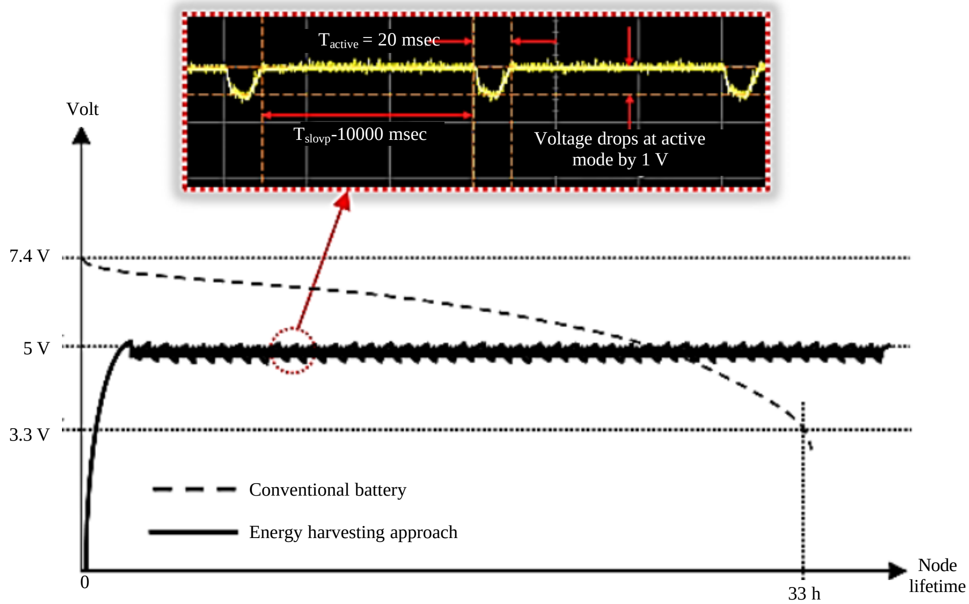


Fig. 7: Thermal energy harvester vs conventional battery as WSN_2_TEH node power source

obtained from the electronic gadgets and mechanical apparatuses. After employing the TEH as a power source for the $WSN_{\_2\_TEH}$ node, the node was up and running all the time as long as there is a sufficient temperature gradient at the Peltier surfaces. With the TEH power source, the only failure in the WSN_2_TEH system might occur regarding to a hardware failure or lack of the temperature gradient. Consequently, therefore the node's lifespan is successfully prolonged.

Figure 7 illustrates the superiority of the TEH on a battery as a wireless node power source. Clearly, batteries have extensive power capacity, contrast to an energy harvesting approach. However, they drained out rapidly, for that reason can't depend on batteries for long life applications "years or decades". Whereas, even though TEH able to recover a quite finite magnitude of energy, however, it can endlessly last. Adding on, it is environment-friendly "green technology", cheaply available and required less servicing. Furthermore, it is obvious that the WSN_2_TEH cause a drop of 1 V due to the active mode activities as previously mentioned. Nonetheless, the proposed power conditioning circuit able to recover the energy during the sleep mode. After all, providing the wireless node with an almost infinite power source.

## CONCLUSION

After a quick briefing to the Seebeck fundamentals and thermal energy harvester, a TEH equivalent circuit is drafted. Based on the equations and the above-mentioned circuit indicates that the recovered Seebeck voltage Vs is directly proportional to the exposed temperature gradient ΔT. Based on that two cascaded peltier units were utilized as a thermal energy harvester. A power conditioning circuit based on TPS61041 is then designed to supply the WSN_2_TEH with the required energy. The experimentations have highlighted that a wireless node lifespan can be further prolonged by utilizing the THE approaches in comparison with a conventional battery which it's last for 33 h only. Besides and as future contributions, more low power units will be investigated as a substitute to the current wireless node architecture. Develop a smart algorithm will be considered to manage the node power source.

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