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APPLICATION OF THERMAL ENERGY HARVESTING IN POWERING WSN NODE WITH EVENT-PRIORITY-DRIVEN DISSEMINATION ALGORITHM FOR IOT APPLICATIONS

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Abstract

Energy Harvesting (EH) has become a crucial part of self-powered autonomous systems, particularly for Wireless Sensor Network (WSN) nodes and the Internet of Things (IoT) sensors. The main advantages of exploiting Energy Harvesting approach lies on its portability, scalability, and low maintenance, as it reduces the dependency on batteries, therefore offers a sustainable and long-term solution for wireless monitoring over a wide area and a large number of sensor nodes. This paper discusses the use of Thermal Energy Harvesting (TEH) approach to power up a wireless sensor node for IoT applications. Wireless node $WSN_{\_1\_TEH}$ consists of MEGA328P as the main MCU, nRF24L01 wireless module, and DHT22 sensor. The TEH system consists of two thermoelectric generators with DC-DC boost converter based on MAX757 and an 8200μF storage capacitor. In the experiment, the TEH system was set to function as the only power source for the sensor node; for comparison of its performance with a 7.4 V rechargeable lithium polymer battery-powered counterpart, by operating for 40 hours continuously. In order to reduce power consumption, the $WSN_{\_1\_TEH}$ node was equipped with an energy-aware Event-Priority-Driven Dissemination algorithm. It was developed to manage the $WSN_{\_1\_TEH}$ operation and to make the sink station able to detect a missing wireless node within the network, which will guarantee the nodes integrity detection. This algorithm will send out data packet based on event or priority, every 20 s of sleeping period. Besides power saving, it also reduces the overall network traffic. Based on the findings, the overall power consumption of this node is 39 mW in "active with transmission" mode, 28-32 mW in "active without transmission" mode, and only 23 mW when operating in "sleep" mode.

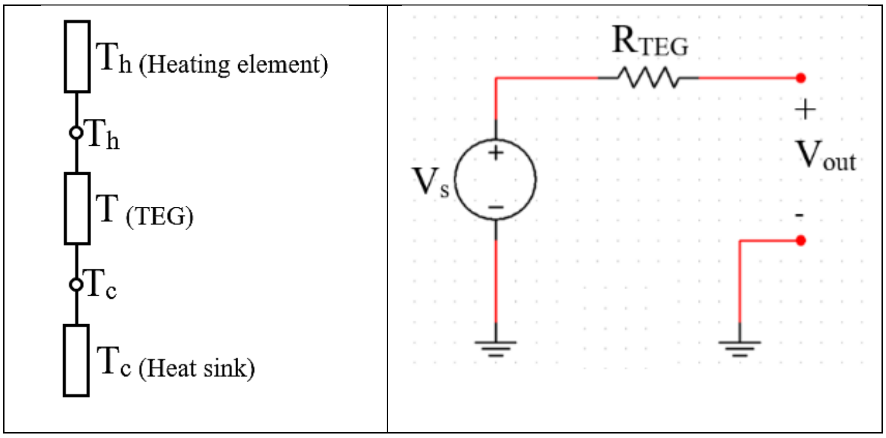
Keywords: Event-priority-driven Dissemination algorithm, Internet of things, Node integrity detection, Power condition circuit, Thermal energy harvesting, Wireless sensor network.

1. Introduction

One of the key advantages of the WSN is that they are flexible and easy to be installed, most importantly, easier to maintain in a large number spreading across a wide area [1]. On top of all, the energy source of the WSN, or more recently for IoT sensors, is the most crucial and challenging technological hurdle that still needs to be overcome for scalable and sustainable WSN. Batteries are a commonly the dominant energy source for WSNs, but not the optimal choice because their lifetime is limited and battery leakage can pose serious environmental pollution. Consequently, the node within WSN will be out of service and unable to accomplish its assigned role once its power source drained out. Therefore, the wireless sensor node is useless whenever its battery has depleted, unless its power source is replaced. For that reason, many R&Ds regarding WSN intended to alleviate battery depletion and extend the lifespan of the node by reducing the energy usage of the node. That can be achieved by utilizing low power components for the node hardware [2, 3], or by exploiting energy-aware routing protocols algorithms software [4, 5]. However, batteries sometimes experience current leakages, which, lead to the self-depleting even though they are not in use. Therefore, WSN nodes, which are powered by batteries frequently, have a limited lifespan due to the battery flaws. In contrary, WSN nodes, which, utilize EH approach as main power supply essentially have almost an infinite lifespan, and a system failure may only occur due to other factors such as physical hardware damage or the absence of ambient energy (such as heat energy, which, this paper focuses on). This type of WSN nodes, which, employs EH as a substitute power source rather than batteries, is a more reliable solution for applications that require long-term operation (up to decades) nodes, or for installation in an environment where battery replacement is an impractical solution.

1.1. Seebeck effect and thermal energy harvesting

The Seebeck effect is a phenomenon discovered by Thomas Johann Seebeck in the 1800s [6]. In this case, the temperature difference between two dissimilar electrical conductors or semiconductors (a combination of "p_{type}" and "n_{type}" pairs) produces a voltage difference between the two substances. When heat is applied to one of these two substances, the electrons on the hot side of the material will be more energized than on the cold side. The electrons will flow from the hot side to the cold side in the "n_{type}," while the holes will flow from the hot side to the cold side in the "p_{type}". Once these pairs connected to an electrical circuit, a Direct Current (DC) will flow through that circuit. This Thermoelectric Generator (TEG) can be simply modelled as a thermal model, represented by thermal resistors connected in series, which, imposes some resistance in the way of heat flow, as shown in Fig. 1(a). It starts with the heat power source ($T_{h\ (Heating\ element)}$), then it flows through the TEG device ($T_{(TEG)}$). Finally, a heat sink is attached to the other surface of the TEG to sink out the temperature to ($T_{c\ (Heat\ sink)}$) by distributing the heat to the ambient. The electrical model, as shown in Fig. 1(b) is based on Seebeck voltage Vs, generated by the TEG in series with its internal resistance R_{TEG} [7, 8].



(a) Thermal model. **(b) Electrical model.**

Fig. 1. Thermoelectric generator equivalent circuit.

The TEG open circuit voltage generated at the terminals can be calculated as:

$$V_s = \int_{T_c}^{T_h} \left(S_B(T) - S_A(T)\right) \tag{1}$$

where S_A and S_B are the Seebeck coefficients, and T_h and T_c are the temperatures of the two junctions. The Seebeck coefficients are non-linear as a function of temperature and depend on the conductors' absolute temperature, material, and molecular structure. If the seebeck coefficients are effectively constant for the measured temperature range, Eq. (1) can be approximated as [7, 8]:

$$V_s = \alpha \Delta T \tag{2}$$

where $\alpha = (S_A - S_B)$ is the Seebeck coefficient, and $\Delta T = (T_h - T_c)$ represents the temperature difference on the TEG surfaces. From Eq. (2), it can be seen that the Seebeck voltage Vs, harvested by the TEG is directly proportional to the applied temperature gradient ΔT by assuming the Seebeck coefficient α is constant. Since the proposed $WSN_{\_1\_TEH}$ has been targeted to be used in a temperature gradient of below 100ºC, and to reduce the prototyping cost. A Thermoelectric Cooler (TEC) module has been chosen rather than TEG module in this research, due to the fact that a TEC module can be function as well as a TEG module in low temperature gradient (below 100ºC), add on a TEG module is 15 times more expensive than a TEC module [9].

1.2. Related work review

Due to the rapid developments in thermoelectric materials and structures, heat to electrical energy recovery by Peltier TEC's module has promising features such as long life cycle, no moving parts, simplicity, and high reliability. Therefore, it is very reliable as a substitute for conventional batteries as the power supply for low power autonomous sensor nodes. The Energy Harvesting efficiency is not the main concern as far as the ambient free energy is recovered. Furthermore, the low harvested voltage it can be easily overcome by means of developing a very smart ultra-low voltage boost converter and power management unit [10-12]. Usually, heat is used to produce mechanical rotation in turbines that are equipped with a generator; which is one of the traditional mechanisms to generate electrical power. This is not the only way of generating electrical power by utilizing heat. TEH is being utilized as an alternative of the traditional mechanism. In 1998, Seiko introduced the world's first thermo-electric watch, named Seiko Thermic cal.6C12. This thermic watch is considered the first application ever of Thermal Energy Harvesting to a consumer product [13]. The wristwatch utilizes thermic that generates power using the difference of the temperature between the wrist and the atmosphere. It can harvest 22 μW from about 1K temperature gradient between the wrist and the environment at room temperature. The harvested power used to recharge a 4.5 mAh li-ion battery besides driving the watch itself [14].

Since then, the interest on TEH has been growing, and more investigations are being conducted. Ibragimov et al. [15] moved a step forward, as they succeeded to harvest up to 500 μW of electric power, by developing a thermoelectric generator directly embedded in an aluminium mould. Rozgic and Markovic [16], presented a thin-film array-based TEH, fabricated in a 0.83 cm2 footprint, along with a power management unit integrated into 65 nm CMOS. His prototype was targeted for biomedical applications, where it achieved 645 μW output power harvested in-vivo from a rat implanted. Meanwhile, Prijić et al. [17] designed a system that can harvest a total of 2 mW of electrical power at ΔT=25ºC to power up a wireless sensor node meant for temperature measurement. Abbaspour [18], presented a unique wireless sensor node powered via TEH. This node was equipped with three selectable active modes and two low power modes, to control the nodes' power consumption. The node consumed 59 mW, 42.4 mW, 0.0026 mW for transmitting, receiving, and sleep mode, respectively. Other researchers developed a novel ultra-low power management circuit for an autonomous multisensory system for agricultural application powered by an EH [19]. They succeeded to harvest about 110 mV/°C and increase the system lifespan by 130 hours. Dalola et al. [20] presented another application of TEH, where they made use of the heat gradients (above 9 ºC) generated by hot walled-in pipes to power up an autonomous sensor system for Radio Frequency (RF) communication. The harvested power was about 130 mW. Their system was designed to read the temperature data and logged it into a non-volatile memory. More applications of utilizing TEH can be seen in [21-25].

2. Low-Level Heat Resources Survey and The Characterization

A mini survey was conducted to investigate various low-level (i.e., less than 150ºC) heat sources. According to Nesarajah and Frey [9], at this amount of temperature, the TEC module has conversion efficiency as good as a TEG. Therefore, TEC as a cheaper alternative can be utilized rather than the TEG module. These heat sources can be categorized as household electrical appliances, offices devices, and machinery, as reported in Table 1. Which are considered good sources of heat for the application of TEH because they operate almost non-stop such as computers, power supplies, monitors, air compressors, refrigerators, etc. Two channels thermometer used to conduct this survey. Table 1 shows that the tested devices generally emit heat from 46ºC by laptop charger, up to 142ºC by the automobile engine during their operating time. All these heat energies are cooled down by the use of heatsinks and then channel-wasted to the environment. Instead of simply being wasted, TEC module can be utilized to make use of the released heat energy and recovered it into a little magnitude of electrical energy, which is sufficient to operate low-power electronic devices.

Table 1. Low-level heat sources survey.

Resource	Temperature
Lab power supply, Metrix AX502	66ºC
Electric water kettle	70ºC
Laptop charger (HP Pavilion dv6000)	46ºC
Steam pressure cooker	133ºC
Tefal cooking pot	102ºC
85" inch TFT-LCD TV panel	57ºC
Refrigerator gas compressor (Toshiba single doors GR S180N)	59ºC
Air compressor (Hitachi 0.2LE-8S0)	110ºC
National aircon. CS-C93KH, 2.7 kW capacity, outdoor unit	48ºC
Core2 Duo 6600 CPU @2.4 GHz	63ºC
A10-6800K	74ºC
Core i7-2600K	72ºC
Core i7-4770K	67ºC
AMD Radeon R9 290X GPU	94ºC
AMD Radeon R9 290 GPU	91ºC
NVidia GTX 970 (EVGA)	71ºC
Car engine	142ºC
Car hood	98ºC

According to our findings in [26], regardless of one or more TEC, they will all recover the same voltage at ΔT=5 ºC. Meanwhile, cascading more TECs' will not guarantee more effect on the V_{out} as increasing the ΔT. A temperature gradient of ΔT=60ºC the V_{out} will be increased only by 0.5 V with every stacked TEC. Based on that, a couple of off-the-shelf TEC's [UT15, 24 Laird XC31] stacked together had been used in the experimental setup. Since the TEC module produces high current, the stacked TECs were electrically connected in series in order to increase the output voltage rather than the current. A heating element in size of 7.5×6.5 cm was used to resemble real temperature from the tested devices. It was driven by a variable DC power supply in order to control its heat gradient, and generate a different heat range at the TEC module hot surface. On the cold surface, a cubical shaped heat sink with the size of 8×7×6 cm was used to cool down the TEC module. A thermal paste was applied to both surfaces of the TEC to guarantee there would be no unwanted air gap. Then, the open circuit V_{out} was recorded by using a voltmeter. Figures 2 and 3 show how the TEC module was sandwiched between the heating element and the heatsink and the experimental layout of the TEH respectively.

Based on the findings and according to Eq. (2), the TEC modules were able to recover DC voltage from 0.28 V up to 2.5 V in a linear manner, which was directly proportional to the applied temperature gradient, where ΔT was increased within the range of 5ºC up to 60ºC. This matched Eq. (2) by assuming the Seebeck coefficient α is constant. Figure 4 depicts the recovered voltage from the two TEC modules at the different ΔT gradient. Since the room temperature is about (25-30) ºC and according to Table 1 readings, the temperature gradient ΔT=35ºC was chosen to complete the research. At this point, the two TECs were able to recover 1.3 V at open circuit, and 43 mW of power at 15 Ω as clear in Fig. 5.

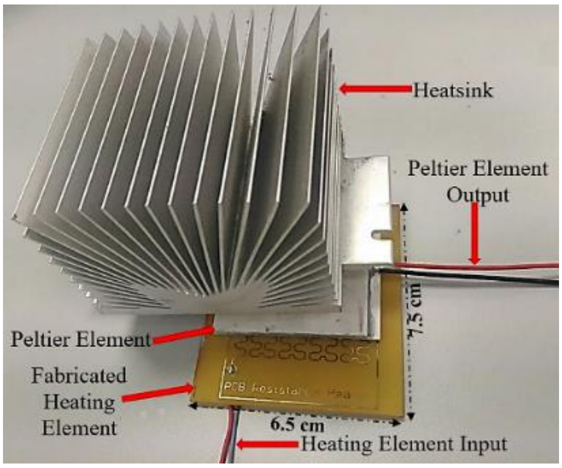


Fig. 2. Thermal Energy Harvesting TEH layout.

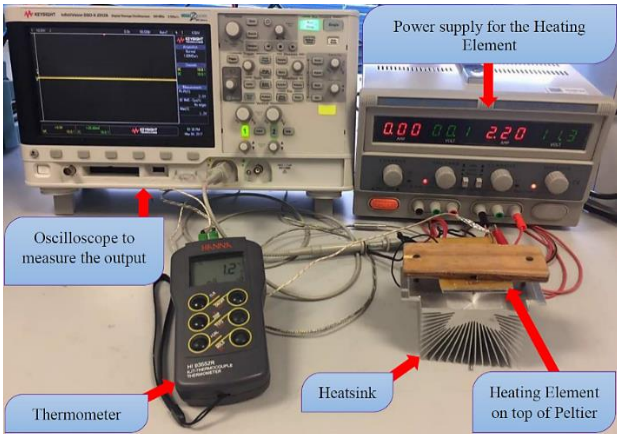


Fig. 3. EH evaluation experimental setup.

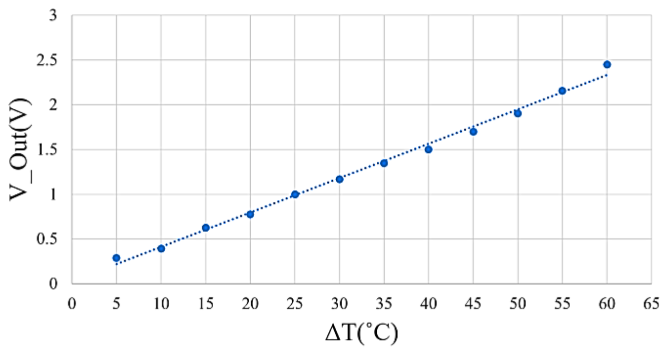


Fig. 4. DC V_{out} harvested from two TEC modules at different ΔT.

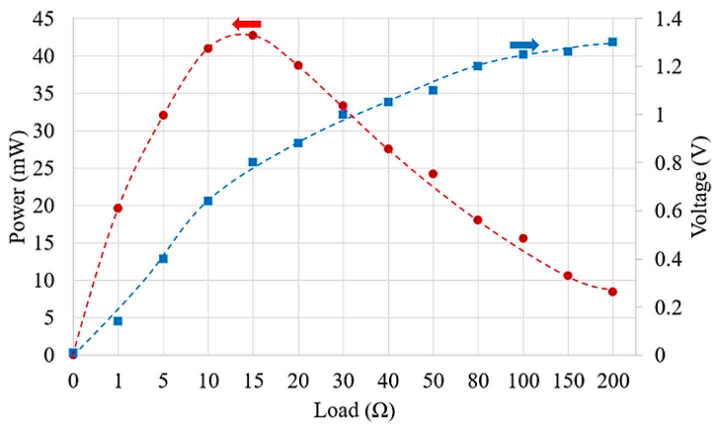


Fig. 5. The recovered power via the two TEC modules at *ΔT*=35°C.

3. Wireless Sensor Node Hardware/Software Architecture

In this study, a fully autonomous wireless sensor node $WSN\_{}_{1\_TEH}$ has been designed in two phases. The first phase is the hardware architecture phase, where the node consisted of a low-power CMOS 8-bit AVR microcontroller ATmega328P. A digital-output relative humidity and temperature sensor dht22 was connected to the mentioned MCU via Serial Peripheral Interface (SPI) to perform temperature measurement. The measured data was then transmitted to the next node via nRF24L01, a single chip radio transceiver 2.4-2.5 GHz ISM band. Since the $WSN\_{}_{1\_TEH}$ was designed to be fully autonomous and powered via EH approach, a power conditioning circuit based on MAX757 was designed in order to boost up the harvested voltage. It was able to start operating at a low voltage of 1.3 V DC harvested by the TEC modules at a temperature gradient of ΔT=35°C. Apart from the circuit components shown in Fig. 6, a NSR0320MW2T1 Schottky diode was used for $D1$. This Schottky barrier diode was chosen based on its own high current handling capability, and low forward voltage performance. Since the MAX757 supports adjustable output, a voltage divider of ($R1$=33 kΩ, $R2$=10 kΩ) was connected to its feedback pin to regulate the output to slightly above 5 V. This voltage would be stored in an 8200 μF10 V capacitor (the charging time is less than 20 s) before supplying it to the rest of node components. Figures 6 and 7 illustrate the architecture and the fabrication respectively of the proposed WSN_{1_TEH}.

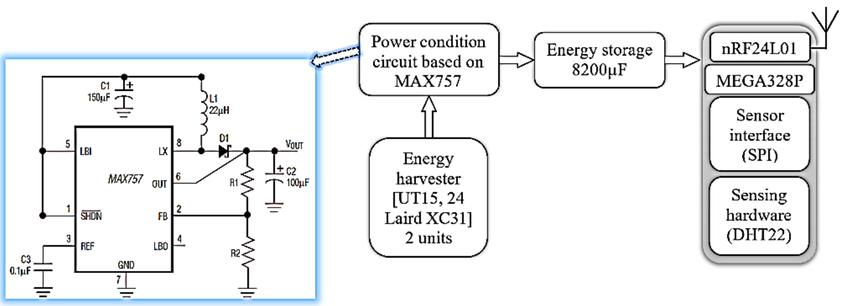


Fig. 6. Proposed WSN_{1_TEH}, wireless sensor node architecture.

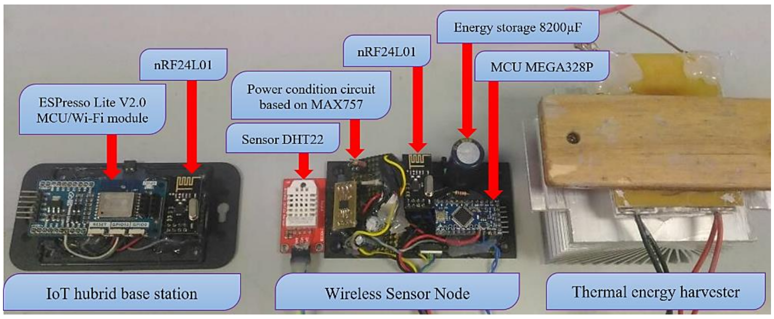


Fig. 7. Fabrication of the WSN$_{_1_TEH}$, TEH, and the hybrid sink station.

The second phase of the WSN$_{_1_TEH}$ design is the software phase. Since it will be powered by the EH approach, its software should be aware of the energy and reduces the power consumption. In this case, an improved algorithm had been developed based on the "Event-Driven Dissemination" (EDD) (Data pushing) technique. Utilizing the data pushing technique should make the sensor node intelligent enough to decide whether the event worth to be reported to the sink station or not. Where the redundant data transmissions will be minimized. Most literature focus on improving detection accuracy [27], data package delivery mode when the geographical information is not available [28], data flow management [29, 30], and energy saving event-driven protocols [31, 32]. However, they did not consider that the sink station could not receive more information about the event. Moreover, it could not differentiate if there was no event to trigger the sensor node, or the node was down, due to power depletion. As it cleared in Fig. 8, where can clearly notice that the node will go into a sleep period whenever it could not find an event of interest, without any transmission.

Consequently, a new algorithm called "Event-Priority-Driven Dissemination" (EPDD) has been developed to transmit the data package based on event occurrence or package priority. Upon detecting an event of interest, the algorithm will assign high priority to that package and transmit it immediately. Otherwise, it will keep increasing the package priority with every normal reading cycle, and then transmit the package when high priority achieved. This algorithm has three levels of package priority; Low, Medium, and High with representations, 1, 2, and 3 respectively.

The scenario of the proposed algorithm is as follows: If there is enough power being supplied by the power conditioning circuit to turn on the wireless node, at the first stage, the algorithm will ask the operator to set a threshold of two values, which are minimum and maximum, representing the safe data range. Then, it will assign high priority to the first package. After that, it will let the MCU go into sleep mode for 20 seconds. This sleeping interval is to allow the power conditioning circuit to build up the power in the storage capacitor for the next wake-up period. The MCU then reads the data from the sensor via the SPI interface directly after it is awake, process it, then it will check whether the data is within the safe range. In case it is so, the algorithm will move on to check the priority, and since the first package priority is assigned to high, it will transmit the package immediately via nRF24L01, reset the priority counter, and set the MCU to sleep again. The algorithm will periodically repeat the sequence of reading the data from the sensor, process it, check whether it is within the safe range, and check the priority to decide whether to transmit or discard the data package. Figure 9 illustrates the flowchart of the proposed algorithm.

As a conclusion of the proposed Event-Priority-Driven Dissemination algorithm:

- If the sensor node detects a reading out of its safe threshold value, it will assign high priority to that package and transmit it directly.
- If the sensor node detects a reading within its safe threshold value, it will increase the data packet priority and discard the transmission.
- The sensor node will keep discarding the data packet transmission until its priority becomes high, then transmit it, and reset the priority counter.

Utilizing this algorithm in $WSN_{\_1\_TEH}$ will make it smart by deciding whether to send or discard the data package, which will reduce the overall node power consumption, compared to the continuous/periodic dissemination algorithm. Moreover, this algorithm will guarantee that the sink station is able to detect a missing wireless sensor node due to power depletion or hardware fault and notify the operator. Furthermore, it will reduce the network traffic load in the overall wireless sensor network. Table 2 illustrates a showcase of the node performance according to the TEH availability and the data condition, with the response in the sink station side when utilizing the proposed EPDD and the typical EDD algorithms.

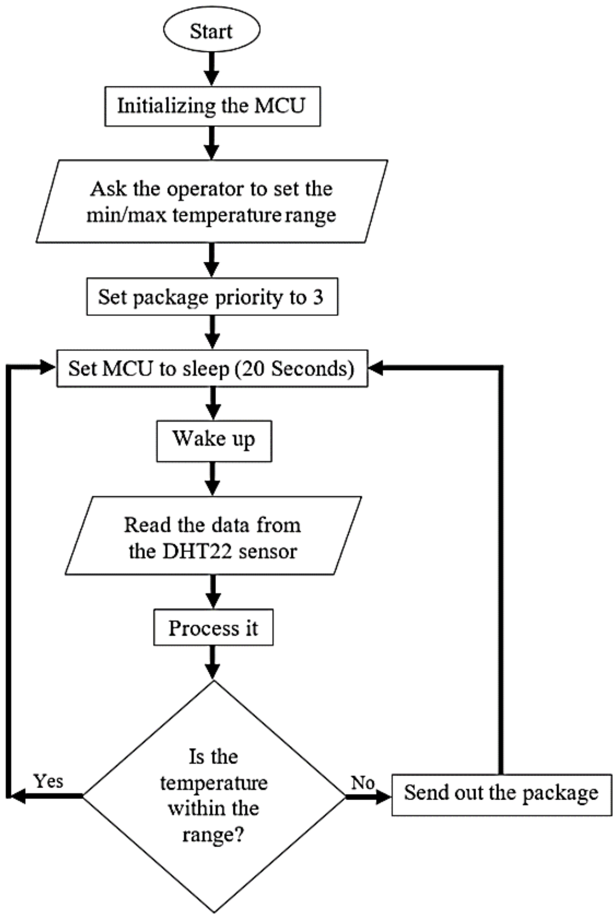


Fig. 8. The typical Event-Driven Dissemination algorithm [34-37].

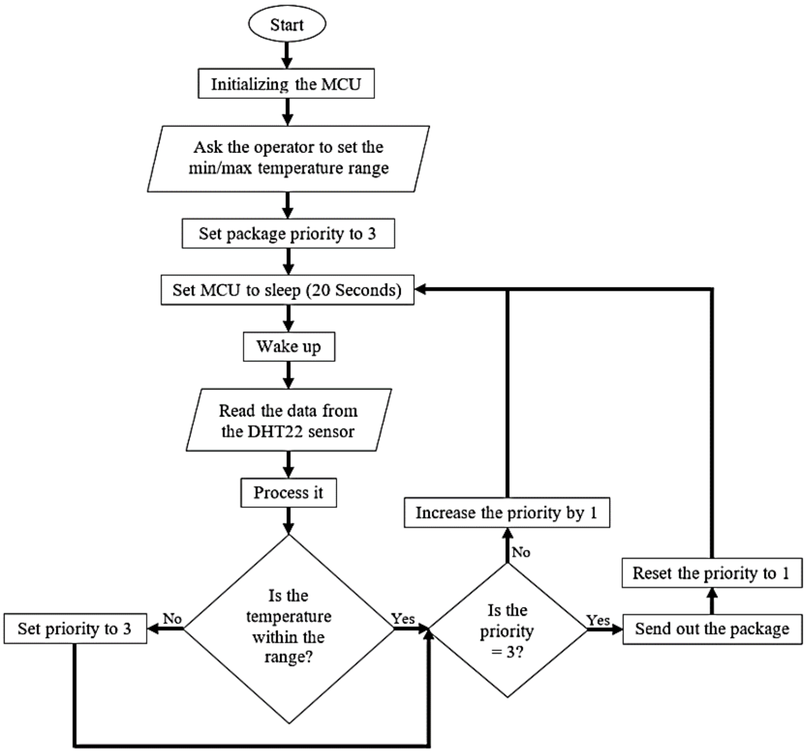


Fig. 9. The proposed Event-Priority-Driven Dissemination algorithm.

Table 2. Wireless sensor node performance at different conditions and algorithms.

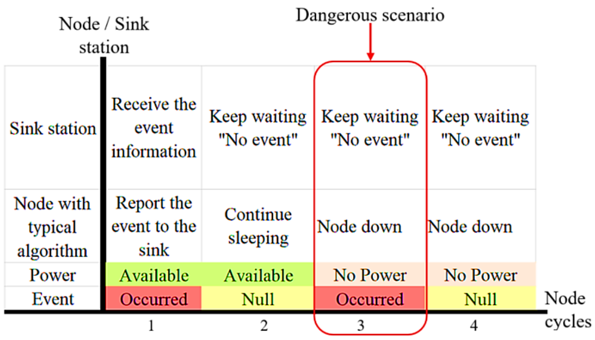
		Typical EDD algorithm		Proposed EPDD algorithm	
THE status	**Data status**	**Node action**	**Sink station**	**Node action**	**Sink station**
Available	In the range	No action, the node back to sleep mode again	Keep waiting since no package coming from the node "No event"	Keep increasing the priority with each wake-up cycle, and transmit the package if high priority is achieved	Receive the node data, "node alive"
Available	Not in the range	Transmit the package	Receive the event information	Transmit the package	Receive the event information, "node alive"
Not available	Whatever	Inactive	Keep waiting since no package coming from the node "No event"	Inactive	Wait for 3 cycles, if no data received, then a "node missing" will be declared

An experiment had been conducted in a controlled environment to examine the performance of the proposed algorithm. The experiment utilized the same node/sink station hardware shown in Fig. 7. Two wireless sensor nodes developed, which, each one equipped with a temperature sensor. The nodes role here is detecting and reporting the environment temperature changes. The first node was programmed with the typical Event-Driven Dissemination algorithm shown in Fig. 8, whereas, the second one programmed with the proposed Event-Priority-Driven Dissemination algorithm that shown in Fig. 9. Then, they had been deployed in the same location to test the nodes' integrity performance at different scenarios.

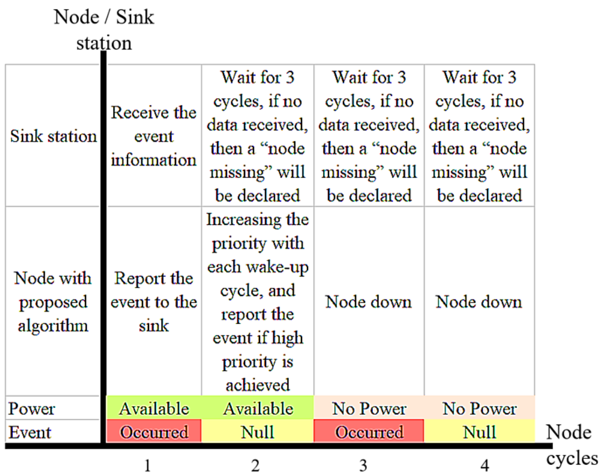
Figure 10(a) shows the experiment outcomes for the first node with the typical EDD algorithm. It shows that when the power is available for the wireless node, it performs well and reporting the occurred event to the sink station. In this case, the node is subjected to sudden temperature changes and it successfully reported the change of event to the sink station. The sink station alarmed the operator for events' precaution. However, the dangerous scenario comes when the node power went down, where at this situation the sink station was not giving any alarm to the operator even though the sensor node was again subjected to sudden temperature changes. The sink station in this stage of the experiment showed no event occurred, which is in fact due to a node down not a normal event as clear in the third cycle of Fig. 10(a). These two scenarios were repeated more than 3 times for data reliability, and with each time the typical EDD algorithm showed a 0% nodes integrity detection.

For the second node that was armed with the proposed EPDD algorithm, it undergoes the same scenarios as the previous one. The experimental outcomes revealed that when the node power is available, it successfully reporting the event occurrence to the sink station whenever the environment temperature changed. In the case where the node power went down, it showed an excellent response from the sink station in detecting the node power down situation. Whereby, the sink station was always expecting a package from the node after every three cycles, otherwise, it will declare a node down and alarm the operator, Fig. 10(b). These two scenarios also were repeated more than 3 times for data reliability, and with each time the proposed EPDD algorithm showed a 100% nodes integrity detection.

The algorithm cycle with power consumption is illustrated in Fig. 11. The proposed wireless node has three different levels of power consumption depending on its active mode. The first peak from the left is representing $WSN_{\_1\_TEH}$ inactive and is transmitting the data package, which will consume about 39 mW. The next peak is after the node is awakened from a 20 seconds sleep, but this time the read data is assumed within the safe range, so the node will increase the priority counter by one only without transmitting, and then go into sleep mode again. In this mode, the $WSN_{\_1\_TEH}$ consumes about 32 mW of the stored electrical power. Lastly, when the node wakes up again and by assuming the read data is within the safety range again, the wireless node will increase the priority counter by one, discard the data package, and go to sleep again. Here the node will consume 28 mW only. Consequently, for the next cycle, either the node will directly transmit out the data package due to the read data might be out of the safe range, or the package priority counter is already high.



(a) Typical EDD algorithm.



(b) Proposed EPDD algorithm.

Fig. 10. Wireless sensor node integrity detection performance.

From Fig. 11 can see that after the node has finished transmitting the data package and consumed the highest power, it will go into a sleep mode for the 20s to allow the power conditioning circuit to accumulate power for next active period. Note that even though at the second peak the node is only reading the data without transmitting, it still consumes relatively high power because the energy storage has been exhausted due to the consumption of the first peak mode, and has not recovered yet. The third peak is the lowest because the previous mode does not consume much energy. Moreover, in Fig. 11 can see that even though the WSN$_{_1_TEH}$ is set to sleep most of the time, it still consumes relatively high power about 23 mW. This power is obviously a wasted since the node does nothing but sleeping during this period. This issue can be considered in future work, by designing an updated version of WSN$_{_1_TEH}$ to isolate the wireless module and the other peripherals from the node during the sleeping period to save the power, besides lengthening the sleeping period.

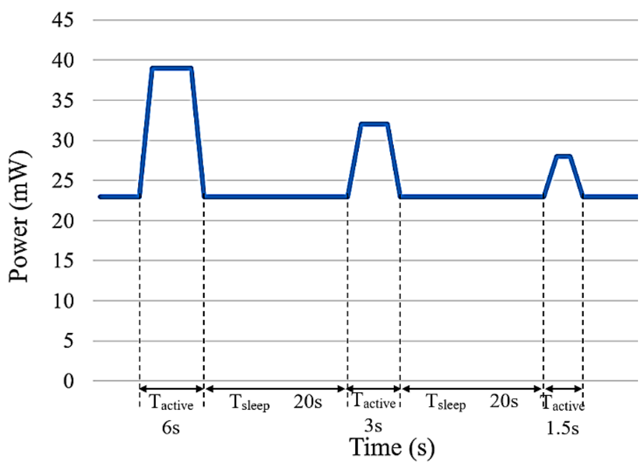


Fig. 11. The proposed wireless sensor node power consumption.

For the sink or the base station, is designed based on ESPresso Lite V2.0, which has an integrated low power 32-bit Tensilica MCU, 10-bit ADC, TCP/IP protocol stack, and Wi-Fi 2.4 GHz, support WPA/WPA2 [33]. This is the core MCU of the sink station and the Wi-Fi module, to upload all the received data to the cloud for telemetry monitoring purposes. It is also equipped with a nRF24L01 wireless module so that it can talk to the other wireless sensor nodes, as its clear in Fig. 7. An AC adapter is used as a power supply for the sink station.

4. TEH versus Battery as WSN Node Power Supply

A comparison had been conducted to confirm the feasibility of the TEH approach as a wireless node power supply. This is also to prove the concept that EH is a successful substitution to the conventional power supply battery. Accordingly, the TEH, power conditioning circuit, and energy storage as shown in Fig. 6 had been replaced with a 7.4 V rechargeable lithium polymer battery with 500mAh capacity from KingMax, as shown in Fig. 12, to power up the $WSN_{\_1\_TEH}$.

Fig. 12. The used lithium battery from KingMax.

The performance of the node with both power supplies was then recorded. The battery was able to make the $WSN_{\_1\_TEH}$ node survive for about 40 continuous working hours until it fully depleted and not able to boot up the MCU at all. This was because, in the meantime, the battery voltage was below the minimum working threshold of the presented node, which was about 3.3 V, as shown in Fig. 13. Hence, the wireless node was completely out of service and battery replacement was required. On the other hand, when replacing the WSN_{1_TEH} battery with the proposed TEH, its lifespan had been significantly extended to almost infinite; and node system failure would only occur due to physical hardware damage or absence of ambient energy source (in this case is the temperature gradient). Figure 13 presents a comparison between the battery and the proposed TEH as the WSN_{1_TEH} node power supply.

Batteries indeed have large power capacity compared to the EH technique, but they depleted rapidly, hence cannot be trusted to be used for long-term applications (years or decades). Although EH technique supplies very limited amount of energy, it works in an intermittent manner almost forever. Furthermore, it is environment-friendly (green technology), cheap, and requires less maintenance. Based on the graph in Fig. 13, the battery started with a very large power of 3.7 W, then it started to lose its capacity until its voltage dropped below 3.3 volts, and the wireless node went out of service. In the TEH, notice that there was a drop in the voltage about 0.6 V due to the wireless node activity and the transmission of the data package. However, the power was sufficient to power up the node to perform its task accordingly. Furthermore, the power management circuit was capable of recovering the voltage when the node went to sleep mode, allowing the node to have an almost infinite power supply.

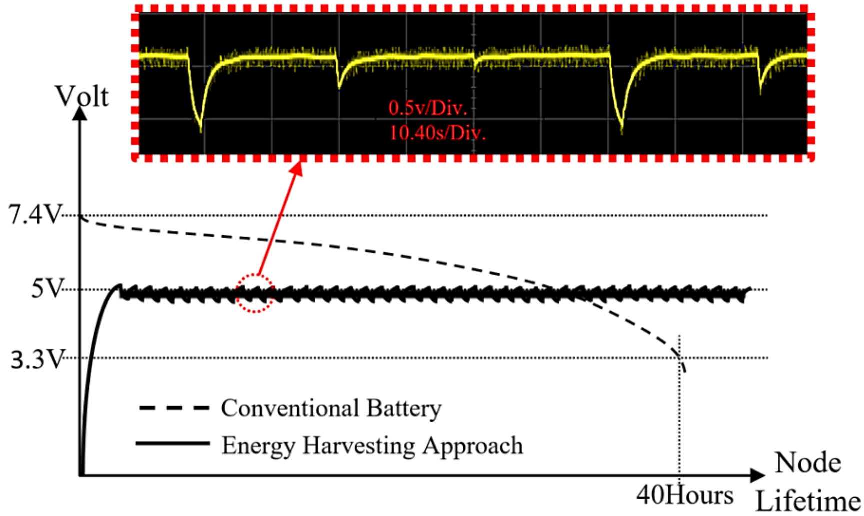


Fig. 13. Battery vs. TEH approach in powering up the wireless sensor node.

5. Conclusions

Since the power supplied from batteries is not sustainable for supporting wireless sensor nodes and Internet of Things sensors for long-term applications, an autonomous self-powered wireless sensor node is desirable, as it can be spatially deployed without the need of battery replacement over time. This paper has presented the utilization of low-level heat dissipated from electronic devices and mechanical machines as the potential heat sources for electrical power generation using TEC. This concept is suitable for powering the autonomous system WSN_{1_TEH} that was developed in this work, which, consists of a DC-DC boost converter, a microcontroller, a sensor and a transmitter, acting as a complete wireless sensor node. In the experiment, the wireless node lifespan has been significantly improved by utilizing the TEH technology, compared to battery power source, which is only able to support the node for a finite period of time. The Event-Priority-Driven Dissemination algorithm was developed to manage the WSN_{1_TEH} operation and to make the sink station able to detect a missing wireless node within the network, which will guarantee the nodes integrity. This algorithm will reduce the network traffic load in the overall wireless sensor network. The outperforming EPDD algorithm is 100% guaranteed the nodes integrity detection within the network, comparing to the typical EDD algorithm in which, 0% guaranteed the nodes integrity detection.

Nomenclatures

R_{TEG}	TEG module internal resistance (Fig. 1), Ω
T_{active}	Wireless sensor node active time (Fig. 11), s
T_{sleep}	Wireless sensor node sleep time (Fig. 11), s

Greek Symbols

α	Seebeck coefficient
ΔT	Temperature gradient, °C

Abbreviations

CMOS	Complementary Metal Oxide Semiconductor
DC	Direct Current
EDD	Event-Driven Dissemination algorithm
EH	Energy Harvesting
EPDD	Event-Priority-Driven Dissemination algorithm
IoT	Internet of Things
ISM	Industrial, Scientific and Medical radio bands
MCU	Microcontroller
RF	Radio Frequency
SPI	Serial Paraphernal Interface
TEC	Thermoelectric Cooler
TEG	Thermoelectric Generator
TEH	Thermal Energy Harvester
WSN	Wireless Sensor Network
WSN_{1_TEH}	Wireless Sensor Node Rev. 1 based on TEH

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