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Research Article

An Integrated Hybrid Energy Harvester for Autonomous Wireless Sensor Network Nodes

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Profiling environmental parameter using a large number of spatially distributed wireless sensor network (WSN) NODEs is an extensive illustration of advanced modern technologies, but high power requirement for WSN NODEs limits the widespread deployment of these technologies. Currently, WSN NODEs are extensively powered up using batteries, but the battery has limitation of lifetime, power density, and environmental concerns. To overcome this issue, energy harvester (EH) is developed and presented in this paper. Solar-based EH has been identified as the most viable source of energy to be harvested for autonomous WSN NODEs. Besides, a novel chemical-based EH is reported as the potential secondary source for harvesting energy because of its uninterrupted availability. By integrating both solar-based EH and chemical-based EH, a hybrid energy harvester (HEH) is developed to power up WSN NODEs. Experimental results from the real-time deployment shows that, besides supporting the daily operation of WSN NODE and Router, the developed HEH is capable of producing a surplus of 971 mA·hr equivalent energy to be stored inside the storage for NODE and 528.24 mA·hr equivalent energy for Router, which is significantly enough for perpetual operation of autonomous WSN NODEs used in environmental parameter profiling.

1. Introduction

WSN can be defined as a spatially distributed sensors network that is used to monitor certain environmental parameters, such as chemical composition, temperature, pressure, movement, displacement or contamination, and induced vibration, and to collectively relay the sensed data to the data center using wireless network [1]. Recent improved networks are capable of performing bidirectional data transmission; therefore, modern WSN is capable of controlling sensors actively and providing instant feed-back based on collected data. The inspiration behind a WSN NODE development was outlined long before for military application, for instance, object presence detection and security surveillance [2].

WSN received enormous research interest across the globe. WSN deployment involves thousands of WSN NODEs distribution around a specific area with some distinct feature for each NODE. The density of deployed WSN NODEs largely varies based on the specific application. Table 1 shows some example of WSN prototype deployment with density of deployment.

One of the visions of WSN is autonomous long-term monitoring of the environmental parameters (such as moisture, temperature, nutrient, and dissolved oxygen) and a key limiting factor for WSN NODEs is the availability of the required power. The long-term targeted benefit from WSN deployment is to provide the future generation with a better and cleaner earth. Hence, WSN should not contribute to increasing greenhouse gases at any stage of its operation.

Currently, most of the WSN NODEs deployed in outdoor environment are powered up using battery since it is a widely established technology and is relatively inexpensive. However, battery-powered WSN NODEs are not suitable for a long-term deployment due to the limited capacity [3] and periodic replacement requirement. In order to address the limited-lifetime problem, many solutions have been

Table 1: Example of some prototype WSN deployment [7].

Application	Type	Distinct feature	Scale and density
Island monitoring	Environmental monitoring	Data storing; web-based access	32 NODEs per square km area [8]
Container tracking	Tracking	Monitoring inside container	14000 container per ship [9]
Detection of flood	Disaster management	Prompt warning; condition monitoring	200 NODEs, 1 per 50 meters [10]
Artificial retina	Health	Image identification; real-time processing.	100 sensors per retina [11]
Human monitoring	Health	Security alerts with high quality	Several NODE per person [12]
Target identification	Military	Real-time object identification	Random NODE [13]
Machine condition monitoring	Machinery	Data aggregation and machine lifetime projection	Tens of NODE per machine [13]
Object tracking	Military	Collaborative processing	Seven NODE per proximity [14]
Tire pressure	Automobile	Real-time feedback for safety	Depends one vehicles size [15]

proposed [4, 5]. These solutions lengthen the lifetime of WSN NODEs by reducing power consumption, such as duty-cycle of operation, though the improvement is only a constant factor and does not solve the limited-lifetime problem. Renewable energy sources, such as solar radiation, vibration, human power, and air flow, can be used to solve this problem, as a recharger means to provide power for a long period of time without requiring the replacement of batteries.

In this work we present the development of hybrid energy harvester to eliminate dependency on periodic battery replacement from WSN NODEs and thus reduce human intervention from deployed WSN NODEs. In particular, we investigate power requirement for in-house developed WSN NODEs such as NODE and Router using the novel "Riemann Sum" [6] differential integral-based strategies. Based on the power requirement a hybrid energy harvesting system is developed and presented here. Power harvesting capabilities of the developed system and energy flow through the sub-NODEs of the developed system are investigated and presented in this research work.

2. WSN NODEs and the Architecture of WSN NODE

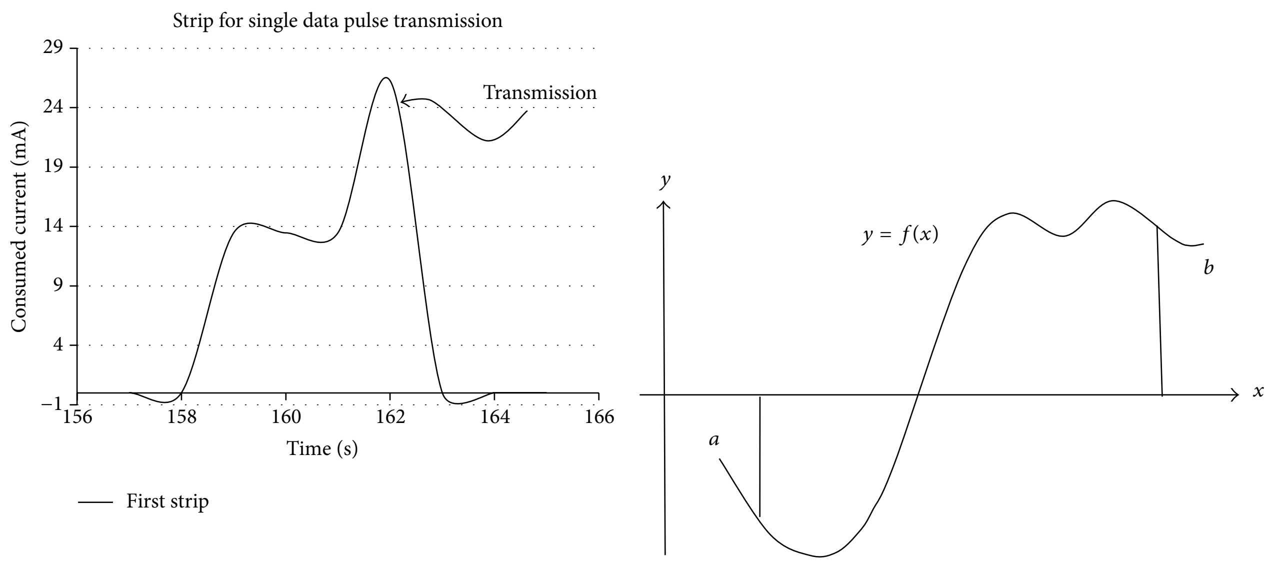
Typically, the general architecture of WSN NODE consists of a sensing unit, microcontroller-based processing unit, data transmission and receiving unit, physical storage, and power source and management unit. The processing unit is used to collect data from the sensors and is capable of processing the collected data. The transmission unit is capable of transmitting data through the wireless network. Besides, the receiving unit is capable of receiving the sensed data and information from adjacent NODEs. The core components of WSN are sensors. These sensors are capable of sensing environmental parameters and converting them to electrical signals. WSN performs its operation by using several components termed as NODE, Router, Gateway, and Data-center. Sensors are usually connected with WSN NODE and NODE communicates with Router; these NODE and Router are two components widely deployed in WSN.

2.1. Power Requirement Calculation of WSN NODEs. To calculate power requirement of a WSN NODE from the real-time data, any standard NODE needs to be configured at a known transmission scenario, for example, 1-TX/5 minutes (1 transmission per 5 minutes of operation) or 10-TX/10 minutes, or so on. It could be an accelerated data collection configuration of WSN NODEs. The instant value of consumed current is in need to be logged using source measurement unit (SMU) at an interval of 1 second. Collected data need to be analyzed thoroughly to identify the pattern of power consumption of WSN NODEs.

The methodology involved to determine power consumption of a NODE from a real-time deployment result is based on the "Riemann Sum" [6] definite integral by estimating an area of strip. The approach to estimate a particular area from this type of strategy involves estimation of area, volume, and time with finite sums. Here, the word "sums" refers to a value that is obtained by multiplying certain functional value by the duration of intervals. In order to express a large sum in compact form sigma notation is used as follows where k are the n number of intervals of rectangle area a:

$$\sum_{k=1}^{n} a_k = a_1 + a_2 + a_3 + \cdots + a_{n-1} + a_n. \quad (1)$$

In WSN application, higher magnitude of power is consumed when WSN components, such as WSN NODE, transmit certain information to the WSN Router or when WSN Router transmits certain information to the WSN Gateway. In such transmission, the required voltage remains fixed for the entire period of operation; the only variable parameter is the current which varies over time. If current drawn by the WSN NODEs is further analyzed over a certain period of time and we interconnect the instant value of current drawn by WSN NODEs, an area of strip formed which occupies an area equivalent to the current consumed by the WSN NODEs for that certain transmission. For example, an area of strip is shown in Figure 1(a) which is equivalent to the drawn power by WSN NODEs which transmit data to the adjacent Router. It is to be noted that WSN NODE consumes significantly high



(a) (b)

Figure 1: (a) Example of current consumption of a WSN NODE for transmitting a single data pulse to the adjacent WSN Router. (b) Arbitrary continuous functions for a close interval of a to b.

current, while it remains in active mode. But inside active mode, WSN NODE draws maximum current (e.g., 26 mA) during transmission, while the NODE consumes significantly different amount of current for the rest of the active mode operation period as shown in Figure 1(a).

From Figure 1(a), it is clear that, by plotting the value of consumed current over a period of time and summation of the values, an area of strip equivalent to the amount of power/energy consumed by the WSN NODE can be determined. Now to measure the value under the strip, the methodology used is termed "Riemann Sum" as mentioned earlier [6]. According to this methodology, to measure the area, an arbitrary continuous function $f(x)$ is used, which resides in a close interval of a to b. The function graph is shown in Figure 1(b).

The interval from a to b can be subdivided into small intervals by choosing $n-1$ distinct points. By assuming that those points from a to b are $x_1, x_2, \ldots, x_{n-1}$, $x_0 = a$, and $x_n = b$, where $a < x_1 < x_2 < \cdots < x_{n-1} < b$. Denoting a by x_0 and b by x_n the set becomes $P = \{x_0, x_1, \ldots, x_n\}$ and this is called a segment of a to b. From this segment, n number of closed intervals between a and b as shown in Figure 2 is determined, which has a length of $\Delta x_k = x_k - x_{k-1}$.

In each subinterval the middle points are identified and selected using numerical analysis. The identification is based on chosen number from the kth subinterval denoted by C_k; then, on each subinterval a vertical rectangle that reaches, from the x-axis, to touch the curve at C_k, $f(C_k)$ is formed as shown in Figure 3.

When this rectangle is used to measure the total consumed power/energy, it is certain that the rectangles would reside above the x-axis. These rectangles approximate the region between the x-axis and the graph of the function. Then, on each subinterval, a vertical rectangle that reaches from the x-axis to touch the curve at $(C_k, f(C_k))$ is formed.

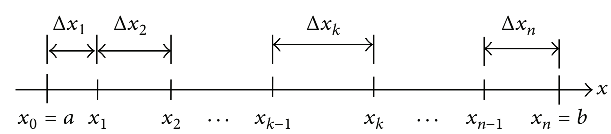


Figure 2: Subdivision of the closed area into variable subintervals.

On each subinterval, the area under the strip can be defined by

$$f(C_1) = \frac{(x_0 + x_1)}{2} * \Delta x_1$$
$$f(C_k) = \frac{(x_{k-1} + x_k)}{2} * \Delta x_k \qquad (2)$$
$$f(C_n) = \frac{(x_{n-1} + x_n)}{2} * \Delta x_n.$$

Therefore, the total area under the strip can be summed up by considering the positive portion of "Riemann Sum" theory which can be depicted by

$$E_{\text{consume}} = \sum_{k=1}^{n} f(C_k \cdot \Delta x_k). \qquad (3)$$

In this work, this methodology is used to measure the energy consumption considering single transmission from the real-time collected data of the developed WSN NODEs.

2.2. Power Requirement Analysis of In-House WSN NODEs. Based on the above-mentioned methodology, an accelerated mode of operation is performed and reported herein, where, for example, a NODE is configured in such way that it transmits 5 sensed data at an interval of 5 minutes. Figure 1(a)

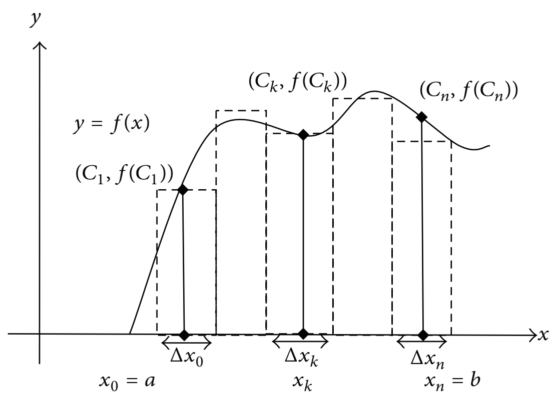


Figure 3: Rectangles extending from x-axis to intersect the curve at certain point.

shows that the active mode operation starts around the 157th second of operation and it ends at the 164th second. The maximum current consumption is 25 mA which occurs at around the 162nd second and this maximum current consumption is significantly different from the current consumption in the entire 157th–164th seconds of operation. During the 157th second, NODE consumed 0.008 mA of current. The NODE is drawing 3 V power from the source. Therefore, power consumed in the 157th second is 0.000024 watt. Similarly, power consumed by the NODE on the 158th second of operation is 0.000021 watt. It increased to 0.040383 watt in the 159th second and NODE continues to draw power from the source until the 165th second. Now, in order to calculate the total amount of power consumed by the NODE, energy consumption for 1 complete operation is calculated and shown in Table 2.

Table 2 shows the pattern of energy consumption of WSN NODEs. From this pattern, power requirement for different transmission scenarios and different WSN NODEs is obtained.

3. Design and Development of Autonomous WSN

Based on the power requirement of the WSN NODEs, we designed and developed solar-based EH that consists of solar energy source converter, energy harvesting circuitry, rechargeable energy storage, step-down DC/DC converter, and integrated NODE or Router. This solar-based EH works as the primary source of energy. Besides, as secondary source of energy we designed and developed chemical-based EH, which consists of chemical energy source converter, energy harvesting circuitry, rechargeable energy storage, and step-down DC/DC converter. However, when both solar energy source and chemical energy source are combined in a hybrid energy harvester, the components become solar and chemical energy sources, dual input harvesting circuitry, rechargeable storage, step-down output circuitry, and WSN components such as NODE or Router as shown in Figure 4.

3.1. Development of the Solar-Based EH. Based on power requirement, a detailed investigation was performed and solar-based EH is developed as the best potential energy harvester establishing fabrication process using all in-house facilities. It is also noteworthy to mention that the substrates used for cell production are discarded scrapped wafer from in-house wafer fabrication laboratory. Characterization results show that the developed cell as shown in Figure 4(b), having 2 cm × 4 cm size, is capable of producing V_{OC} of 0.58 V and I_{SC} of 230 mA (power density 12 mW/cm^2).

3.2. Development of the Novel Chemical-Based EH. The key investigation performed in development of chemical-based EH is to find the suitable electrodes. The key subcomponents of such EH are a pair of electrodes and a membrane in-between the electrodes. In the developed cell, off-the-shelf air-electrode is used as a cathode [16]. To search for the suitable anode that matches well with the air-electrode, four different types of electrodes are fabricated on top of a silicon wafer substrate using aluminum, titanium, platinum, and copper as active electrode materials. Fabrication of electrodes is performed using RF magnetron sputtering process. These four types of electrodes along with air-cathode are used to fabricate the energy harvesting cells. Initially, using all these electrodes, eight EH cells are prepared. Then, to measure the open circuit voltage (V_{OC}) the cells are connected with a 16-channel source measurement unit (SMU) as shown in Figure 5(a).

The reason for this controlled setup is to identify the electrode performance in terms of V_{OC} production. Based on all the above investigations and analyses a functional prototype of chemical-based EH cells is developed. The size of the active electrode in the EH cells is kept at 2 cm × 4 cm. Cells are further connected in a serial (as shown in Figure 5(b)) and parallel fashion.

3.3. Development Consideration for the EH Circuitry. Since the amount of power from solar-based EH or that of chemical-based EH are not consistent and a wide range of input voltage production follows, a suitable energy harvesting circuit is required that can harvest energy from a source that produces voltage in a wide range, which sometimes could be very low. The energy harvesting circuit should have the capabilities to convert the harvested energy to a more suitable form, which can be stored into a rechargeable storage device. As the amount of harvested energy depends very much on the ambient environment, it is not suitable to support the connected WSN Node/Router directly. Therefore, the intermediate energy storage is required, which can store leftover harvested energy and provide continuous power supply to the WSN Node/Router even when there is no ambient energy available. Now, to support WSN Node/Router from the storage, the storage should have capabilities to supply higher voltage than the adjacent Node/Router requirement. Output circuitry comes into action in this scenario by converting the DC/DC downstream conversion of output power from the storage, according to the requirement of adjacent Node/Router. The overall behavior of the hybrid powered energy harvester depends on the design of each component of the system.

TABLE 2: Detailed energy consumption of WSN NODE for 1 transmission.

Operational period (number of seconds)	Analyzed data for the first transmission Average consumed current (mA)	Consumed power (Watt)	Area of strip
157	0.008	0.000024	0.0000225
158	0.007	0.000021	0.020202
159	13.461	0.040383	0.0403905
160	13.466	0.040398	0.0404025
161	13.469	0.040407	0.0596085
162	26.27	0.07881	0.0394245
163	0.013	0.000039	0.000033
164	0.009	0.000027	0.000027
165	0.009	0.000027	
	Energy consumed (J)		0.2001105
	Average power consumed (W)		0.025013813

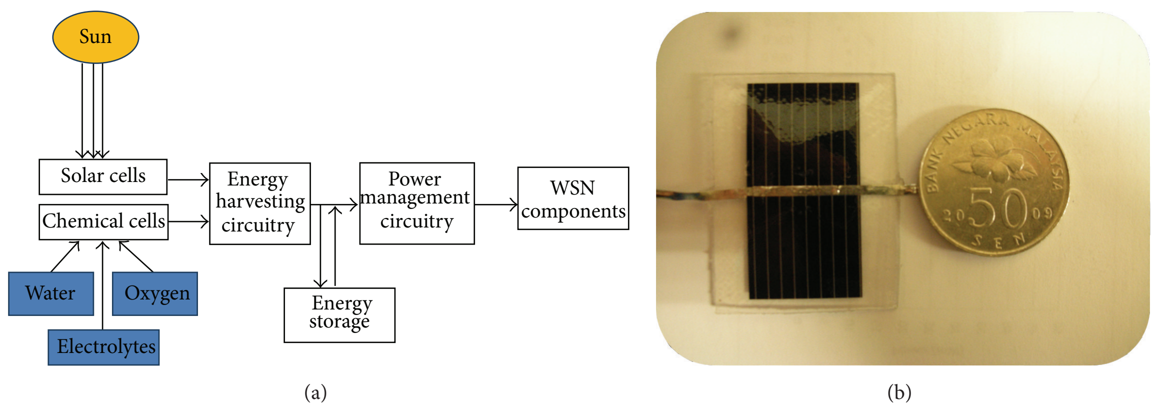


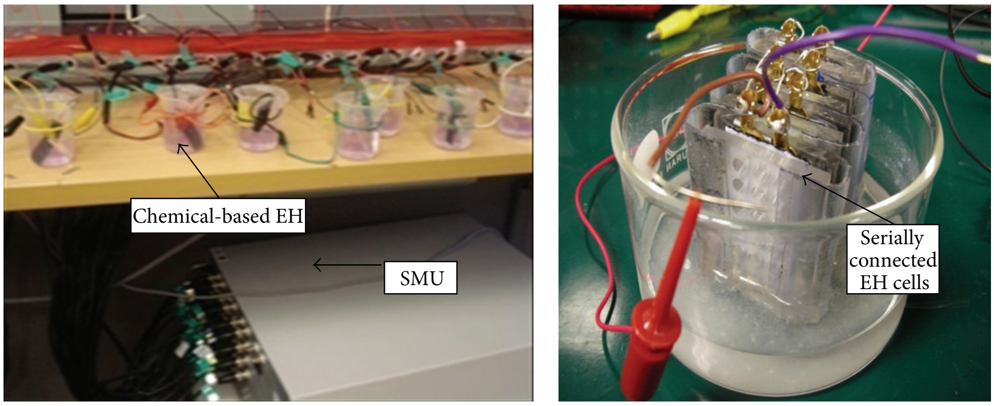
FIGURE 4: (a) Block diagram to develop a hybrid energy harvester-based complete WSN system. (b) Photograph of the solar cell; its dimension with respect to a Malaysian 50 cent coin.

For the energy harvesting circuit design IC LTCR3105 (linear technology 2009) is chosen. This IC is a highly efficient DC/DC stepped up converter capable of operating from a very low range of input voltage (minimum input voltage is as low as 225 mV). The IC has a maximum power point controller (MPPC) integrated with it, which is suitable to operate with both solar- and chemical-based high impedance sources. The MPPC is programmable so that it can maximize the extracted power from the sources.

3.4. Analysis of the Performance of the Chemical- and Solar-Based EH. Developed chemical- and solar-based EH have a wider range of harvesting capabilities. Number of harvesting cells with the circuitry determines the output power from the cell. For example, one chemical-based EH cell can produce V_{OC} of 0.98 V and I_{SC} of 52 mA, while a number of eight cells are capable of producing V_{OC} of 7.52 V and I_{SC} of 72 mA. Output harvested power from the cell also varies from 5.76 mW to 48.048 mW based on the number of serially connected cells. Similarly, a single solar-based EH can produce V_{OC} of 0.585 V and I_{SC} of 230 mA, while eight cells can produce V_{OC} of 4.6 V and I_{SC} of 140 mA in the presence of the bright sun. The summarized capabilities of the developed cells are presented in Table 3.

3.5. Development of the Energy Harvesting and Power Management Circuitry. Since the amounts of power from EH cells are not consistent and a wide range of input voltage production follows, a suitable energy harvesting circuit is required that can harvest energy from a source that produces voltage in a wide range, which sometimes could be very low. The energy harvesting circuit should have the capabilities of converting the harvested energy to a more suitable form, which can be stored into a rechargeable storage device. As the amount of harvested energy depends very much on the ambient environment, it is not suitable to support the connected WSN NODE/Router directly. Therefore, the intermediate energy storage is required, which can store leftover harvested energy and provide continuous power supply to the WSN NODE/Router even when there is no ambient energy available.

Now, to support WSN NODE/Router from the storage, the storage should have capabilities to supply higher voltage than the adjacent NODE/Router requirement. Output circuitry comes into action in this scenario by converting the DC/DC downstream conversion of output power from the storage, according to the requirement of adjacent NODE/Router. The overall behavior of the hybrid powered energy harvester depends on the design of each component of the system. Figure 6 shows the developed energy harvesting



(a) (b)

FIGURE 5: Experimental setup to proof-of-concept of chemical-based EH. (a) EH cells are connected with SMU. (b) Photograph of developed chemical-based EH cells connected serially.

TABLE 3: Power producing capabilities of chemical- and solar-based EH cells.

Cell dimension [2 × 4 cm each]	Chemical-based EH cells					Solar-based EH cells				
	V_{OC} of the cell (V)	I_{SC} from the cell (mA)	Maximum extracted power (mW)	V at Max P (V)	I at Max P (mA)	V_{OC} of the cell (V)	I_{SC} from the cell (mA)	Maximum extracted power (mW)	V at Max P (V)	I at Max P (mA)
Single	0.98	52	5.76	0.32	18	0.58	230	96	0.481	200
2 cells	1.625	62	11.88	0.54	22	1.152	180	163	0.984	167
4 cells	3.64	64	21.55	1.128	19.1	2.3	167	314	2.0	157
8 cells	7.52	72	48.048	2.31	20.8	4.6	140	461	3.9	118

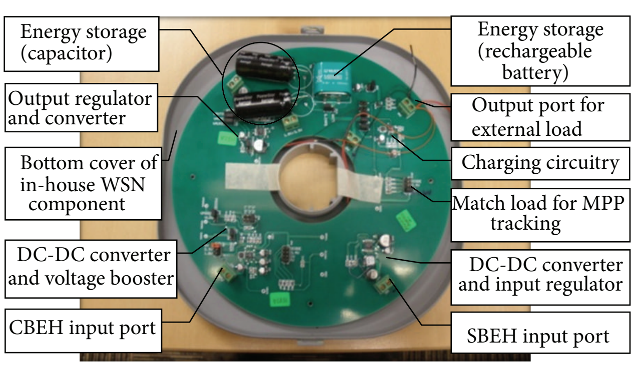


FIGURE 6: Photograph of the developed energy harvesting circuit with integrated storage.

circuit and its components which is integrated with the developed EH cells.

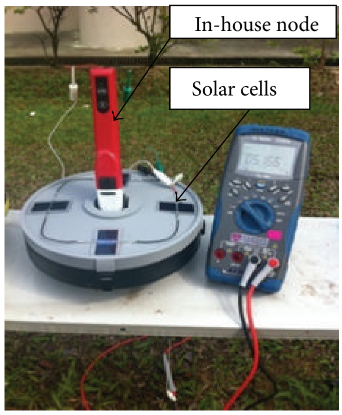
For hybridization/integration of all these subcomponents, common platform development is required. For microscale WSN components this common platform can be on top of a single substrate, but for macroscale WSN components this platform need to be placed inside a casing. In this research work, for in-house WSN components a macroscaled casing is designed and implemented as a platform where energy harvester, storage, circuitry, and WSN components are placed robustly. Besides, the feasibility of integrating different energy harvester and storage in a single platform is also investigated.

4. Deployment of the Autonomous EH-Based WSN NODEs and Performance Evaluation

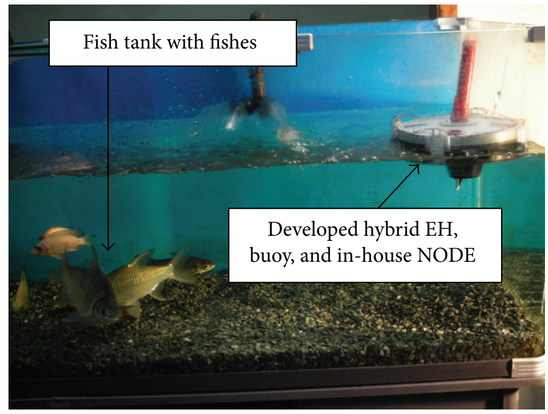
It is to be noted that the harvested power from the chemical-based EH is continuous. The amount of harvested power is low compared to the solar-based EH, but their continuous harvesting capability is essential to integrate it as the secondary source of energy. A photograph of the solar-based EH integrated with the in-house developed WSN NODEs is shown in Figure 7(a). Apart from this, a complete prototype of the deployed system containing hybrid EH is shown in Figure 7(b).

Once the WSN NODEs are connected with the hybrid EH, the system runs successfully because the harvested power is continuous in nature and minimum harvested power from the hybrid EH is well above the requirement of the WSN NODEs. Table 4 shows the cumulative energy flows in detail through the subcomponents of hybrid energy harvester-based autonomous WSN NODE and Router at different time of a day.

From the evaluation of the implemented energy harvester, obtained capabilities along with the dimension, ambient source requirement, and harvesting modes are summarized in Table 5.



(a)



(b)

Figure 7: (a) Photograph showing the solar-based EH is charging the energy storage. (b) Prototype of hybrid energy harvester-based autonomous WSN NODEs.

Table 4: Cumulative energy flows through the subcomponents of hybrid EH-based autonomous WSN NODE and Router at different time of the day.

Real-time deployment	WSN NODE					WSN Router				
	Energy flow (in kilojoules)									
Time on the day of operation	NODE consume	Discharge from battery	Solar EH produce	Chemical EH produce	Hybrid EH produce	Router consume	Discharge from battery	Solar EH produce	Chemical EH produce	Hybrid EH produce
Discharge before dawn 00:00:00–07:15:30	0.318	0.469	0.017	1.150	1.167	0.661	0.602	0.017	1.150	1.150
Transition 07:15:30–09:10:25	0.407	0.533	0.261	1.442	1.703	0.837	0.693	0.261	1.442	1.450
Recharge 09:10:25–17:30:20	0.768	0.533	6.517	2.718	9.234	1.600	0.693	6.517	2.718	4.695
Saturation 17:30:20–19:15:25	0.843	0.573	6.782	2.983	9.765	1.746	0.753	6.783	2.983	4.993
Transition 19:15:25–20:18:30	0.890	0.648	6.788	3.149	9.937	1.840	0.847	6.788	3.149	5.160
Discharge 20:18:30–00:00:00	1.045	0.884	6.798	3.694	10.491	2.159	1.147	6.797	3.694	5.705

Developed hybrid EH-based autonomous WSN NODEs are deployed in several locations successfully and this eliminates the requirement of battery replacement and human intervention. Besides, environmental parameters monitoring the system can be deployed in several other application domains such as, but not limited to, forest fire monitoring and structural health monitoring.

5. Conclusion

In this paper, a thorough investigation has been carried out to design and implement a hybrid energy harvester that is capable of harvesting energy from ambient sources to power-up the WSN NODEs. The proposed energy harvesting system is developed successfully with detailed contemplation of all subcomponents, integrated with in-house developed WSN NODEs and deployed magnificently for profiling environmental parameters. From the power requirement analysis, it is found that, in the existing scenario (10-TX/day), in-house developed WSN NODE and Router with the help of 1200 mA·hr storage can survive only for 3.6 and 0.29 months of operation, respectively. To overcome this issue, solar-based energy harvester cells are developed and integrated with the system. It is found that, for 4 cells having 2 cm × 4 cm size connected serially to charge, the storages are capable of producing 314 mW cumulatively. Apart from solar-based EH, chemical-based EH as a secondary source of energy is developed and integrated with the system and it was found that, by connecting 8 chemical-based EH cells, a total amount of 48.048 mW continuous power can be harvested. From the evaluation of the developed system, it is found that, by powering WSN NODE or Router, hybrid energy harvester produces an additional amount of 10491.93 J (equivalent to 2.91 Wh which is capable of filling-up 971 mA·hr of storage) or 5705.12 J (equivalent to 1.58 Wh which is capable to filling-up 528.24 mA·hr of storage), respectively, sufficient enough

Table 5: Capabilities of the implemented energy harvesters at a glance.

Type of EH	Energy sources and harvesting mode	Cumulative harvested energy	Equivalent energy in Wh	Applicable for
Solar-based EH	Sunlight, discrete	6,798 J/day	1.89	NODE
Chemical-based EH	Water, oxygen, and electrolytes, continuous	3,695 J/day	1.03	Additional source
Hybrid energy harvester	Sunlight, water, oxygen, and electrolytes, continuous	(With NODE) 10,492 J/day (With Router) 5,705 J/day	(With NODE) 2.914 (With Router) 1.5	NODE and Router

to support WSN NODEs if the ambient solar goes off for the next few days.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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