Introduction to Energy Harvesting for Low-powered Wireless Sensor Nodes

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***Abstract*—**The deployment nature of wireless sensor network warrants the usage of batteries for end node operation albeit with very limited lifetime. However, implementing energy harvesting mechanism allows the sensor node to replenish its energy and thus operate perpetually. This write-up discusses key elements in designing low-powered energy harvesting node. A prototype was created to show the viability of harvesting energy from the ambient in conventional wireless sensor network platform. Results show that the prototype is able to harvest energy with or without the load.

Keywords-energy harvesting; energy scavenging, wireless sensor network

I. INTRODUCTION

Wireless sensor network has been used extensively for automation and wireless solution. Often, due to application requirements, the end node placements necessitate the use of batteries; with limited capacities, as a power source. This paves way for the implementation of sensor nodes with energy harvesting (EH) capabilities to solve the finite energy problem. If the load current consumption is very low, the sensor node can even operate perpetually by replenishing its own energy from energy scavenged from the environment.

A low-powered sensor node does not have a specific definition tagged to it, but from the literature, it is adequate to categorize nodes with 500 mW requirement as low-powered. In this write-up, we have followed this definition for the load, although the energy harvesting source may be expended up to 1 W of power for improving reliability.

In Section II, related literature on energy harvesting node is covered while the design and architecture of the system is discussed in Section III. This is followed by the detailing of the EH prototype and its evaluation in Section IV and V respectively.

II. ENERGY HARVESTING NODES

Traditional EH methods and typical performances are shown in Table 1 [1-5].

TABLE 1. ENERGY HARVESTING SOURCES AND CAPABILITIES

Energy source	Power density
Outdoor solar	10-100 mW/cm^2
Indoor solar	10-100 $\mu W/cm^2$
Piezoelectric	100-330 $\mu W/cm^3$
Vibration (machinery)	100-116 $\mu W/cm^2$ / 200-800 $\mu W/cm^3$
Vibration (human)	4 $\mu W/cm^2$
Thermoelectric (machinery)	1-10 mW/cm^2
Thermoelectric (human)	30-60 $\mu W/cm^2$
Acoustic noise (100 dB)	960 nW/cm^2
Radio Frequency	0.1-0.9 $\mu W/cm^2$
Outdoor wind turbine	3.5 mW/cm^2
Electromagnetic (machinery)	200-1000 $\mu W/cm^2$
Airflow	0.4-1 mW/cm^3

To date, harvesting energy from sunlight remains the most cost-effective way that has led to the maturity of the technology. Although scavenging energy from other elements has gained traction, still, most of them are not yet feasible for electronic devices due to factors such as power output, size and cost.

Related works on EH nodes are tabulated in Table 2, which many are based on the review made by Sudevalayam [6]. The variety of specifications of these works reflects different applications and requirements. However, the basis of an EH system remains almost the same, which will be discussed in the next section.

III. ENERGY HARVESTING SYSTEM ARCHITECTURE AND DESIGN CONSIDERATIONS

An EH system can easily be created by directly connecting the energy harvesting source to the load. However, this creates a very inefficient structure that puts behind scientific values and lacks integrity. Therefore, designers have identified the common architecture for an EH system and the framework of is illustrated in Figure 1. The central part consists of the power management unit (PMU), which is responsible to regulate the power, re-charge the storage element and reduce power transfer inefficiency. Another important criteria for designing the EH system is the compatibility and good match between each block of the architecture. Careful module selection that has close voltage and current usage is a must to ensure less waste of resources. For example, a 100 mW solar cell may not able to power up a 50 mW load reliably due to voltage and current mismatch. The following subsections will discuss in more detail on each part of the EH architecture, excluding the load, for design considerations.

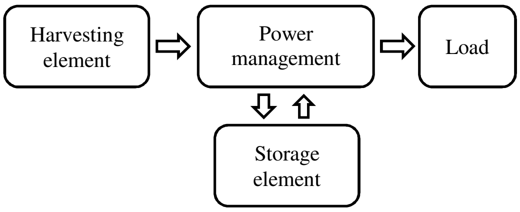

Figure 1. Energy harvesting system architecture

A. *Harvesting Element*

The harvesting module is rated in power, which is essentially based on the formula of P = I * V. Designer must pay attention to the V_{output}, V_{oc}, I_{output} and I_{sc} that represents ideal voltage output, open-circuit voltage, ideal current output and short-circuit current output of a module, respectively. Note that often a module would not be able to perform in its ideal condition therefore reserves must be made to mirror the actual performance.

B. *Power Management Unit*

A battery management system (BMS) often acts as the PMU to efficiently and safely charge the storage media and also allowing higher power transfer efficiency. Besides its traditional operation as a battery charger and regulator, the BMS may also acts as a load balancer to ensure the cells within the battery are within safe operating voltage. A good BMS should have a level of programmability to allow some space for flexibility. Currently, there are many BMS available in the market, for example brands by Texas Instrument (TI) and Linear Technologies, which made circuit designing simpler and quicker.

C. *Maximum Power Point Tracker (MPPT)*

MPPT can be implemented as part of the PMU or as a stand-alone subsystem. MPPT allows maximum power to be harvested from the harvesting element. This is done by combining the optimum current level with the optimal voltage value, as maximizing either one would not produce maximum power. The I-V relationship in solar panels is shown in Figure 2 [18].

Open circuit voltage, V_{oc}, is the maximum voltage of the solar cell when there is no load connected to it and thus no current flows (I=0 A). While the short circuit current, I_{sc}, is the maximum current produced by the solar panel when the module itself is being short-circuited and voltage drops to 0 V. However, in reality, the voltage and current of a harvesting module will always be lower than these values. In solar cells and panels, the MPP is usually around 80% of the V_{oc}. Therefore, a MPPT system will always adjust the I-V values in order to produce the most power output possible from the solar cell.

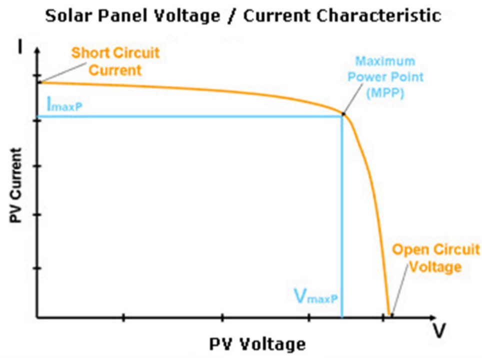

Figure 2. I-V relationship (in yellow) and MPP (in aqua).

TABLE 2. RELATED WORKS ON ENERGY HARVESTING NODES

Node	Solar cell (mW)	Storage type: supercapacitor and/or battery	Voltage range (V)	Deployment strategy	MPPT
Prometheus [7]	130	22 F and 200 mAh Li-Po	1.5 – 4.4	Fixed	No
Everlast [8-9]	450	100 F	2.5 – 2.7	Mobile and fixed	Yes
AmbiMax [10]	400	22 F and 200 mAh Li-Po	2.5 – 4.1	Mobile and fixed	Yes
Heliomote [5]	190	1800 mAh Ni-MH	2.2 – 3.0	Add on-board for Mica2 node	No
ZebraNet [11]	400	2000 mAh li-ion	3.1 – 5.0	Mobile	Yes
Low power adaptive MPPT [12]	Up to 400	300 mAh Ni-MH	1.5- 3.5	Mobile and fixed	Yes
Battery-less sensor node [13]	N/A	3.3 F	5.0 – 10.5	Mobile and fixed	No
Ultracapacitor based EH [14]	10 000	1 F and 7500 mAh	5.0 – 12.0	Fixed	No
SolarBiscuit [15]	150	1 F	3.6 – 5.0	Mobile and fixed	No
HydroWatch / HydroSolar [16]	400	Two 2500 Ni-MH	2.1 – 3.6	Fixed	Yes
SHiMmer [17]	360	250 F	1.8 – 3.3	Fixed	No

D. Storage Element

Even in an EH system, the storage element is equally important, acting as a power source back-up to ensure perpetual load operation. Rechargeable battery is the obvious choice followed by supercapacitor with varying voltage levels, capacities and shapes between them. The most common batteries used for small and low-powered devices are prismatic lithium ion (li-ion) as it has flat, lightweight and acceptable density, suitable for portable usage. Nominally, the li-ion batteries are rated at 3.7 V, with operation ranging from 2.9 to 4.2 V. On the other hand, supercapacitor is often cylindrical in size and too bulky to provide equivalent battery capacities, but may still provide good solution for niche applications.

IV. PROTOTYPE OF THE ENERGY HARVESTING NODE (EHN)

The EHN is made up of two solar cells, a PMU, a rechargeable battery and a wireless sensor node as the load. A single EHN prototype is shown in Figure 3. Two solar cells are connected in parallel to heighten reliability, where each is rated at 500 mW, with V_{oc} and I_{sc} are 4.6 V and 110 mA respectively. Note that a single solar cell would still be able to power up the load per se if needed.

The BQ25504 BMS by TI is selected as the PMU due to three criteria:

a) Allows a level of flexibility in hardware programmability.

b) Includes programmable MPPT feature.

c) Power output is suitable for low-powered application.

The BQ25504 is programmed using resistor networks, to charge the li-ion battery to a maximum and minimum cut-off voltage at 4.11 V and 2.9 V respectively, with 3.7 V being the normal level for load operation.

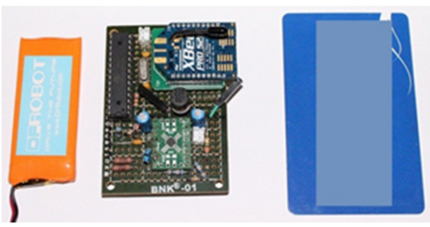

Figure 3. An EHN prototype with batteries detached and a credit card for size comparison.

Alternatively, the battery could also be charged to its maximum 4.2 V but the decision was made to lower the absolute cap to avoid battery stress. The MPPT is programmed to be operational at nearly 80% of the V_{oc}. In normal conditions, the energy harvested will be regulated by the BMS to power up the load and any surplus of resource will be used to charge the battery. Otherwise, the load can also be switched off to focus the energy on battery charging. A 1000 mAh prismatic li-ion battery is assigned the storage element due its small form factor and lightweight.

The load is made up from an Xbee RF module which is connected to an Atmel Atmega328p microcontroller that forms the wireless node. For the sake of stress testing the EHN, a Pro version of the Xbee is opted with maximum power level set in its configuration. The Xbee works in 2.4 GHz and has 95 mA peak transmit and 51 mA receive mode current consumption [19] while the formula for the average current consumption can be found in [20]. The choice of load is not arbitrary; it is actually used for another study and hence won't be detailed.

V. DESIGN EVALUATION

Solar cell is very sensitive towards light intensity and therefore its performance is dependent largely on the availability of clear bright sun. The presence of clouds and haze would affect its voltage and current output, sometimes severely, especially the latter. However in ideal conditions, the EHN performed well and its performances are shown in Figure 3 and 4. With the aim of obtaining 3.7 V battery voltage level, charging with and without load took around 580 and 370 minutes respectively; when the load is switched off, the EHN can focus its harvested power to recharge the battery. On the other hand, if the load is switched on, the node which consumed about 95 mA would effectively cut down about half of the remaining current for recharging the battery, resulting in a 56.7% excess time needed to charge the battery to 3.7 V. The exponential graphs in Figure 3 and 4 can be explained as follows; first, battery has larger capacity at higher voltage, requiring a lot more current to be pushed in and thus taking a longer time to charge up. Secondly, as battery density increases, the amount of charge (current) that can be pushed in is reduced, which shares an analogy to pumping a flat tyre to its full capacity.

The benefit of implementing MPPT is shown in Figure 5. With MPPT activated, the system managed to harvest 7% more power than a non-MPPT setup within 90 minutes of bright sunlight exposure, which in turn would reduce the amount of time needed to charge the battery. The MPPT is also able to work in lower voltage, for example, between 1.5 to 3 V, allowing room for design flexibility.

VI. CONCLUSION

Important elements pertaining to the design of an EH system for low-powered devices has been discussed in Section IV. For validation of the design framework, an EH prototype, named as EHN, has been developed. The prototype was able to harvest sufficient energy to power up the load whilst concurrently charging the storage element. EHN could therefore serve as a general guideline for designing wireless nodes with energy harvesting capabilities.

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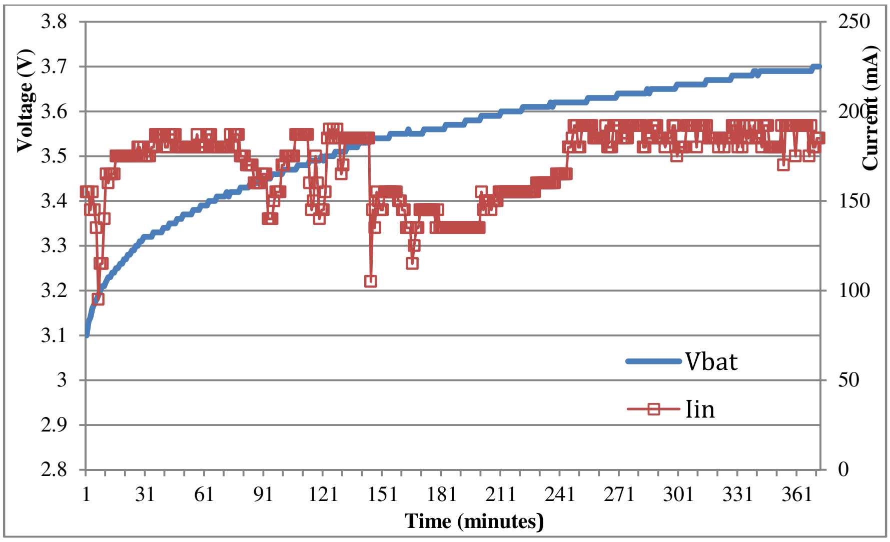

Figure 3. Battery charging without load using 1 W solar cell.

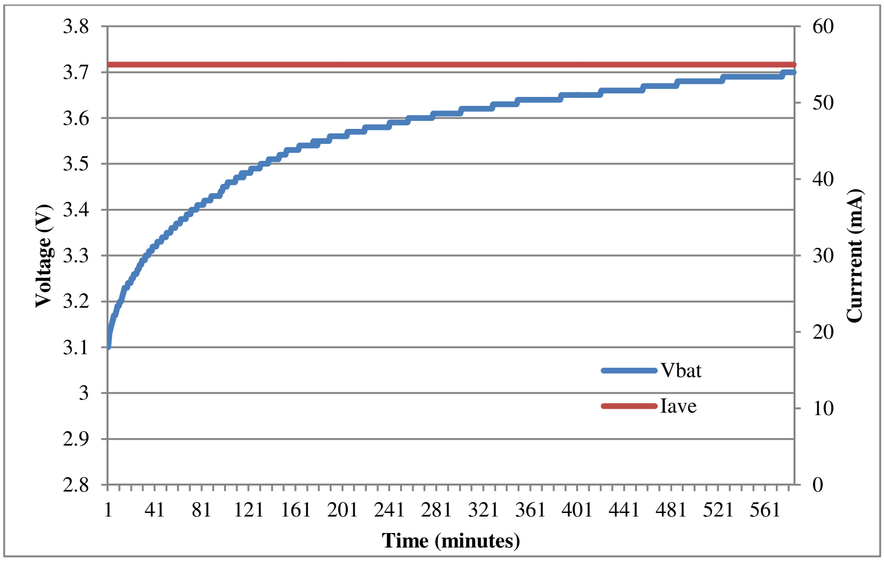

Figure 4. Battery charging by BQ25504 with load connected using 1 W solar cell.

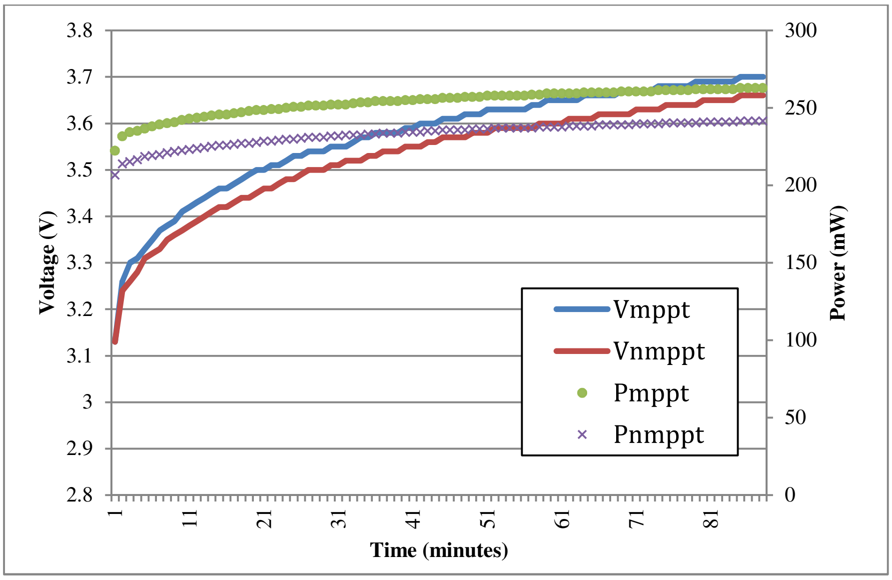

Figure 5. MPPT versus non-MPPT (nmppt) with V_{in} = 4.6 V and I_{in} = 89 mA.