The Design of Sustainable Wireless Sensor Network Node using Solar Energy and Phase Change Memory

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***Abstract*— Sustainability of wireless sensor network (WSN) is crucial to its economy and efficiency. While previous works have focused on solving the energy source limitation through solar energy harvesting, we reveal in this paper that sensor node's lifespan could also be limited by memory wear-out and battery cycle life. We propose a sustainable sensor node design that takes all three limiting factors into consideration. Our design uses Phase Change Memory (PCM) to solve Flash memory's endurance issue. By leveraging PCM's adjustable write width, we propose a low-cost, fine-grained load tuning technique that allows the sensor node to match current MPP of solar panel and reduces the number of discharge/charge cycles on battery. Our modeling and experiments show that our sustainable sensor node design can achieve on average 5.1 years of node lifetime, more than 2× over the baseline.**

I. Introduction

Wireless Sensor Network (WSN) has emerged as a promising platform for many nontraditional applications, such as environmental monitoring, health care and surveillance. A WSN usually contains many low-cost, battery-powered devices ("sensor nodes") that are capable of collecting/processing data, and communicating with other nodes through wireless communication. Sensor nodes are usually left unattended after deployment such that the lifespan of WSN is severely constrained by its energy source, i.e., battery capacity [13].

Energy harvesting allows sensors to scavenge energy from environment and provides an attractive method to extend the lifespan of WSN. Among different energy sources, solar energy has significant advantage of high availability [3] and is drawing interest in WSN research [4]. Energy source of solar-powered sensors can last 10∼20 years [24], which is much longer than that of conventional designs. Furthermore, solar-powered sensors can operate on much higher duty cycles, allowing WSN to achieve better performance and accuracy.

However, removing the energy source constraint alone cannot extend the lifespan of WSN as expected. Our study showed that the following two factors arise as new major obstacles to extending the lifespan of WSN.

a) Memory: Integrating solar energy harvester in a sensor node enables it to operate on heavy duty cycles such as data cryptographic and in-network data processing activities. The previous work by Mathur et al. also reveals that more local data processing (compression and aggregation) helps to reduce communication cost and improve network response time [16]. Since a sensor node only has limited internal RAM storage (512B∼512KB) [1], [20], [30], much of the data processing needs accesses to the external Flash storage, which results in increased write accesses to the Flash.

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Unfortunately, Flash memory has limited write endurance (write/erase cycles), typically 10^5 times [19] before it wears out. For desktop or high-performance computing systems, this issue can be addressed by redundancy and wear-leveling. However they are much less feasible in WSN due to the and capacity limitations. Our estimation shows that a 4MB Flash memory on a solar-powered sensor node may only sustain a few days running some of the benchmark kernels we experimented. Hence, the non-volatile memory on sensor node becomes a constraint on its lifetime.

b) Battery: The amount of solar energy collected by the harvester relies on environmental conditions (e.g. irradiation and temperature), which are often unpredictable. Thus it is necessary to use a small rechargeable battery to store unused harvested energy and to provide energy when solar energy is not available (e.g. nighttime or cloudy days). In this paper, we adopt rechargeable battery instead of supercapacitor due to its low cost, high energy density and small size (which is especially important for sensor node).

Rechargeable battery has limited "cycle durability" (number of discharge/charge cycles). For example, Li-based battery can typically sustain ∼500 times of discharge/charge cycles [2]. This "cycle life" poses another limit on sensor node's lifespan. Furthermore, our modeling and experiments reveal that in addition to the daily discharge/charge cycles caused by nighttime use, the many small discharge/charge cycles during the daytime also have significant impact on battery's cycle life and must be taken into consideration.

c) Sustainable WSN: Although solar-powered WSN sensor node has been proposed in previous works [3], [4], [9], [23], few attentions were paid on the above two concerns that emerge with the introduction of solar energy harvester. We believe that simply adding solar energy harvester onto WSN sensor node will not yield the expected long lifespan, as sensor node's lifespan can be also constrained by Flash memory wear-out and battery cycle life. Hence a **sustainable sensor node** design must take all these factors into consideration.

In this paper, we propose a sustainable sensor node design to address above constraints. We introduce *Phase Change Memory* (PCM) into solar-powered sensor node design to address Flash memory's endurance problem. By exploiting PCM's tunable write width, we devise a low-cost *load tuning* mechanism that can adjust sensor node's power at fine-granularity. This helps to match sensor's working power with solar panel's Maximum Power Point (MPP) at runtime. The proposed design not only improves the utilization of solar energy, but also greatly reduces the number of small discharge/charge cycles, resulting in significantly longer battery cycle life. Our experiments show that our sustainable sensor node design can extend the node lifetime up to 7.6 years, which is about 2× comparing to the baseline.

II. Background

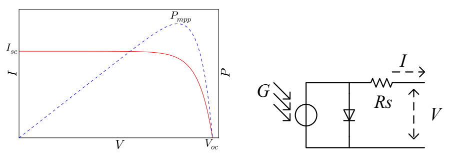
A. Phase Change Memory

Phase-change memory (PCM) is one type of non-volatile memory that uses different physical states (amorphous or crystalline) of phase change material (e.g. $Ge_2Sb_2Te_5$, or GST) to store data. Different physical states of GST have drastically different resistances, which are used to represent 0 or 1 respectively. Writing to a PCM cell is achieved by applying voltage pulse on the cell and controlling its heating/cooling process.

Comparing to Flash memory, PCM has much higher write endurance (10^8 times [31]), faster access time and the ability of random access. As a result, PCM has been proposed as part of main memory in previous works [11], [29], [31].

B. Solar Energy

The output current and voltage of photovoltaic (PV) module has a non-linear correlation. As a result, PV module has a working point at which it outputs the maximum power (Maximum Power Point, MPP). MPP is determined by module parameters such as short circuit current I_{sc} and open circuit voltage V_{oc}, as well as environmental conditions such as irradiation and temperature. To achieve efficiency in energy harvesting, most solar-powered systems integrate some types of MPP tracking mechanisms, e.g., those developed for WSN sensor nodes [3], [4], [21].



(a) I-V, P-V characteristics. (b) Equivalent circuit.

Fig. 1. Photovoltaic module.

C. Battery Cycle Life

Rechargeable battery can only be discharged and charged for a limited number of times, which is referred to as "cycle life" in this paper. A less noticed characteristic is that battery's cycle life also depends on how much it is discharged (Depth-of-Discharge, or DoD) in each cycle [6]. For example, a Li-based battery's cycle life is 500 if DoD is 100% (i.e. the battery is fully discharged in each cycle). If DoD is 10%, on the other hand, battery's cycle life would be about 4700 [2]. Drouilhet and et al. described a prediction model for the correlation between battery's cycle life and DoD [6]. We use this model in our experiments to predict cycle life cost for different DoD values (Section III-C).

III. Sustainable WSN Sensor Node

A. Architecture

Our proposed sensor node design (Fig. 2) is similar to the multiple-supply system (MPS) discussed in [21] (in fact, WSN sensor node is categorized as an emerging type of MPS device in the literature). The Power Control & Distribution unit is responsible for voltage regulation and distribution for all functional components (MCU, memory, sensors, etc.) It also tracks the MPP of the solar panel to maximize the power drawn from environment. Several MPP tracking techniques have been proposed for WSN [3], [4], [21]. In this paper we will focus on *load matching*, i.e. matching sensor node's power consumption with current MPP. Mismatching between load and current MPP will cause either waste of solar energy (if load is lower than MPP), resulting in lower WSN performance; or unnecessary operation time on battery (if load is higher than MPP). The latter case will increase the number of small discharge/charge cycles and impact battery cycle life.

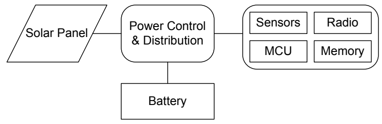


Fig. 2. Architecture of Proposed Sensor Node

B. Memory

We propose to use Phase Change Memory (PCM) in sensor node's memory system, replacing both Flash memory and most of the SRAM. PCM cell is modeled as resistance in a similar way as in [31]. Current and voltage numbers are derived and scaled from [10], and we assume PCM's write latency to be 150ns [11].

Using PCM in sensor node's memory system brings multiple advantages over conventional design, such as better endurance, non-volatility, byte-addressability and tunable write width which allows fine-grained control of write power.

C. Improving Battery Cycle Life

1) Modeling Solar Panel: Photovoltaic module can be described with an equivalent circuit consisted of a current source and a diode, as shown in Fig. 1(b). We model the I-V characteristic of the photovoltaic module (solar panel) used in our experiments with a similar model as in [12] and [28]:

$$I = \frac{G}{G_0} I_{sc}(1 + K(T - T_0)) - I_0(e^{\frac{q(V+IR_s)}{nkT}} - 1)$$

Where R_s is the series resistance of the module, I_0 is the diode's saturation reverse current, K is the temperature coefficient of I_{sc}, n is the ideality factor of the diode, k and q are Boltzmann's constant and the electron charge respectively.

2) Modeling Battery Cycle Life: Rechargeable battery's cycle life (L) has a non-linear correlation with Depth-of-Discharge (D) of each cycle, which can be modeled with equation $L = u_2(\frac{D_R}{D})^{u_0} e^{u_1(1-\frac{D}{D_R})}$, where D_R is the Depth-of-Discharge corresponding to the rated cycle life (e.g. if cycle life is rated against full discharge in each cycle, then D_R is 100%) [6]. We can identify the parameters u_0, u_1 and u_2 by fitting the equation curve with sample data. In our experiments, we use sample data from [2] and fit the equation using Least Squares Fitting to derive the parameters (Fig. 3).

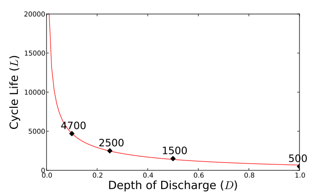
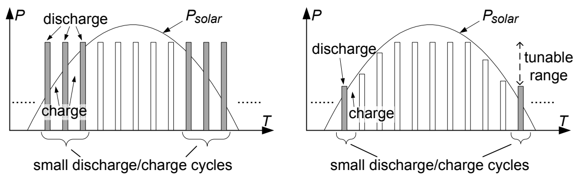


Fig. 3. Battery cycle life vs. depth-of-discharge (DoD).

A solar-powered sensor node can have very different DoD in each cycle. DoD tends to be small during the daytime as battery can be charged promptly after use; while during the nighttime, DoD tends to be larger. In order to predict overall battery cycle life of a sensor node, we define a **Battery Cycle Life Cost Function** $C_{cl}(D) = 1/L(D)$ to tell how much battery cycle life will be "consumed" by a cycle. Battery failure is predicted when accumulated cost $\sum C_{cl}$ exceeds 1.

3) Fine-Grained Load Tuning: A typical sensor node works in a "blink" fashion, meaning that it wakes up periodically, works for a while and goes back to sleep mode again. As shown in Fig. 4, on the one hand, the power consumption of a sensor node appears as a series of short "pulses" over a period of time; on the other hand, the maximal power point (MPP), i.e., the maximal power that can be provided from the solar energy harvester, depends on the environmental conditions and appears as a curve during the daytime. If the requested power is bigger than MPP, the sensor node has to switch to use the battery. Without proper management, a solar-powered sensor node may experience a number of discharge/charge cycles during a day. Too many discharge/charge cycles greatly reduce the battery lifetime and thus shorten the WSN lifespan.



(a) Fixed power consumption. (b) Tunable power consumption.

Fig. 4. Small discharge/charge cycles of solar-powered sensor node.

In order to extend sensor node's battery life, we need to reduce the number of discharge/charge cycles, in particular, during the daytime. Given that switching to battery is inevitable if the requested power is bigger than MPP, it is important to keep the working power below MPP. In our design, we propose fine-grained load tuning by taking advantage of the tunable PCM write width:

- Memory/storage system contributes a significant part of sensor node's power consumption [16], [17], especially for solar-powered sensor node that tends to take heavy duty jobs and perform local data processing.
- PCM's write power can be easily controlled through the use of column mux,which is more responsive and fine-grained than traditional heavy-weight techniques (e.g. DVFS).

Implementation of the tuning scheme is straightforward: upon a write request, the PCM controller selects write width (4, 8, 16, 32, 64-bits) based on currently available solar power. It then generates the masks for the column mux of PCM array to control how much bits are written simultaneously. The information of solar power availability can be polled from the MPP tracker in Power Control and Distribution Unit (Fig. 2). Note that choosing lower write width could increase write latency and hurt performance. However, the impact is tolerable since WSN is usually not very performance critical.

With our fine-grained load tuning scheme, sensor node can avoid many unnecessary uses of battery in daytime, reducing total number of small discharge/charge cycles. As we can see from Fig. 4(a), many small discharge/charge cycles during daytime are caused by the mismatching between load and solar panel output. Although solar energy is available in these blinks (in gray color), sensor node still works under "battery-powered" mode, creating many small discharge/charge cycles. These small cycles, while each has low cycle life cost (C_{cl}), have significant impact on overall cycle life when accumulated. Fine-grained load tuning avoids the use of battery by tuning the power consumed by PCM, and thus removes many small discharge/charge cycles (as in Fig. 4(b)).

Note that not all discharge/charge cycles can be removed in the daytime. When MPP is less than the minimal working power (e.g. early morning), the sensor node still needs to use the battery. In the afternoon, the sensor needs to schedule to fully charge the battery for nighttime use.

TABLE I
BENCHMARKS USED IN EXPERIMENTS.

Benchmark	Description
crc16 [26]	Error detecting code
rc5 [7]	Block cipher
fft [8]	Fast Fourier transform
rle [14]	Run length encoding compression
bubblesort [15]	Bubble sort
quicksort [15]	Quick sort

TABLE II
EVALUATED GEOGRAPHIC LOCATIONS.

Station	Location
SOLRMAP: LMU	Los Angeles, CA
SunSpot1	San Luis Valley, CO
SOLRMAP: La Ola Lanai	Lanai, HI
UNLV	Las Vegas, NV
ORNL	Oak Ridge, TN

IV. EVALUATION

A. Experimental Setup

We use Avrora [27] to simulate a Mica2-like sensor node platform [25]. We collect traces for different benchmark kernels, including compression, cryptography, digital signal processing and basic algorithms. Details of the benchmark kernels used in our experiments are listed in Table I.

We use a 100mAh 3.7V rechargeable battery in our simulation. As discussed in Section III-C, we use a battery cycle life prediction model from [6] and derive the parameters (u_0, u_1, u_2) using sample inputs from [2]. We assume PCM's write power to be 1.22mW per bit (scaled from [10]), and the baseline uses a fixed write width of 64-bits. Power consumption of other components (MCU, radio, etc.) are got from [25]. Total power consumption of the sensor node can be tuned between 121.88mW and 195.08mW. Suppose sensor node has 10% duty cycle, a fully charged battery used in our experiment can sustain the sensor node at peak power consumption for up to 18.5 hours, long enough for a solar-powered device.

We use a 250mW solar panel similar to the SP4-100-8 unit from Plastecs [22], and use the photovoltaic model discussed in Section III-C to compute I-V curve and MPP. Irradiation and meteorological data used by our model are got from the Measurement and Instrumentation Data Center (MIDC) of National Renewable Energy Laboratory [18] (Table II).

B. Evaluation Results

With the use of fine-grained load tuning technique, our sustainable sensor node can reduce much of the small discharge/charge cycles during daytime. Our experiments show that number of small discharge/charge cycles ($DoD < 10\%$) is reduced by up to 85% and 75% on average (Fig. 5).

As discussed in previous sections, the small discharge/charge cycles have significant impact on overall battery cycle life when accumulated. Fig. 6 compares the average battery cycle life (in years) between proposed fine-grained load tuning technique (`TunablePCM`) and baseline. Our sustainable sensor node design achieves an average battery cycle life of 5.1 years, more than $2\times$ improvement over baseline.

In order to achieve expected lifespan in Fig. 6, more memory may be required to provide enough space for wear-leveling. Hence we estimate memory capacity required to match the lifespan in Fig. 6 for PCM and Flash memory. On average, 6.7GB of Flash memory will be needed to match the expected lifespan, while for PCM the requirement is 5.5MB. These results illustrates the economy of our design, not only in terms of extended lifespan but also in terms of memory/storage cost.

An interesting question is what if we simply set the baseline to use minimum write width (4-bit). Although this can also extend battery cycle life, it has following disadvantages: (i) it wastes solar energy that otherwise can be harvested, (ii) it slows down the sensor node due to $16\times$ PCM write latency, and (iii) it increases network response time due to slower processing speed. Fixed 4-bit write scheme is up to 26% slower than baseline (5.6% on average) while our load tuning design is only up to 6% slower (0.5% on average).

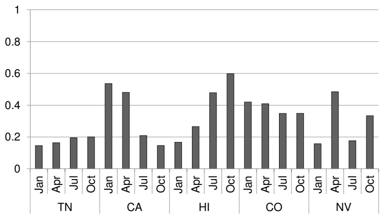


Fig. 5. Number of small discharge/charge cycles ($DoD < 10\%$) normalized to baseline.

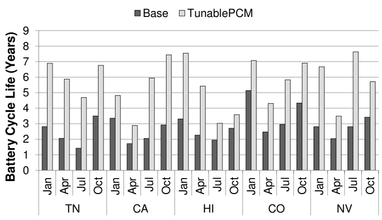


Fig. 6. Battery cycle life improvement with tunable PCM write width.

V. Related Works

Using solar energy in WSN is drawing attention in recent studies due to its prospect of extending sensor node's lifespan. Previous works, such as the use of PV module in WSN sensor node [9], [23] and MPP tracking techniques [3], [4], focused mainly on efficient solar energy harvesting. The sustainability (durability) of sensor node was also studied in [24] and [5]. Both works consider energy source as the only limiting factor of sensor node's lifespan, while in this paper we propose that memory wear-out and battery cycle life must also be accounted for. Our load tuning technique share similarity with Load-Matching Switch [21]. Our work is different in that Load-Matching Switch targets on utilization of solar energy, while our work identifies and addresses a different problem (lifespan of sensor node). Using PCM's adjustable write width, our technique also provides finer granularity in load tuning.

VI. Conclusion

We propose a sustainable WSN sensor node design using solar energy and Phase Change Memory. We reveal that sensor node's lifespan is not only limited by energy source but also by memory wear-out and battery cycle life. We propose to use PCM in sensor node's memory system to solve Flash memory's endurance issue. We then exploit PCM's adjustable write width and propose a fine-grained load tuning technique, allowing the sensor node to match its power demand with current MPP of the solar panel. Through our modeling and experiments, we observe that our proposed design can reduce 75% small discharge/charge cycles. As a result, lifespan of sensor node is extended to 5.1 years on average, more than $2\times$ improvement over baseline.

VII. Acknowledgment

This work is supported partially by NSF CNS CAREER-0747242 and CNS-1012070.

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