When They Are Not Listening: Harvesting Power from Idle Sensors in Embedded Systems

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Abstract—Ambient energy harvesting is a well-known technique in wireless sensing systems. To minimize energy consumption, such systems are typically designed to be heavily duty-cycled with long idle times and are characteristically lightweight in computation. Often, these systems contain a dedicated energy harvesting transducer that is independent of the sensing sub-system. As a result, any output energy from the sensor ends up being unused (and hence, lost) when the system is in idle state. This work proposes a novel system architecture and corresponding hardware platform, 
\textit{SEnergy}, in which the energy harvested from a sensor during idle time is utilized to power the system. \textit{SEnergy} is based on an ultra-low power charge pump circuit that boosts input voltages as low as 330mV. We successfully demonstrate our proposed architecture with an RF-capable (2.4GHz ISM band) sensing platform utilizing a photovoltaic sensor as the sole energy source. We evaluate our approach on two applications, namely adaptive transmission of sensor data and providing an uninterrupted power supply to an on-board real time clock.

I. INTRODUCTION

Micro-scale energy harvesting is a well-known technique for powering low-power embedded systems. In a micro-scale energy harvesting system, a transducer (\textit{i.e.}, energy harvester) converts other forms of environmental energy into electrical energy. Often, the energy being harvested is stored in a storage element (\textit{e.g.}, battery, supercapacitor) until it reaches a usable amount since the power output of the harvester may not always be sufficient to operate a target system. Therefore, micro-scale energy harvesting is well-suited for a duty cycled application that allows sufficient time for energy harvesting.

Cyber-physical systems (CPS) are an integration of computational and physical processes \cite{1} such as wireless sensor networks for environmental sensing \cite{2}. They employ a large number of networked sensor devices to effectively monitor the physical world at a fine granularity \cite{2, 5, 6}. Usually, an energy storage element, such as a battery, is used for powering CPS devices to ease large-scale remote deployment. Hence, the devices are typically designed to be computationally lightweight and heavily duty-cycled to minimize energy consumption. These devices are also often equipped with passive sensors that produce output power proportional to the physical signal being sensed. However, when a sensor output is not being sampled by the target system, the output power from the sensor is unused and, hence, wasted. This work proposes the idea of harvesting the otherwise unused power from a sensor when it is idle and using it to operate the target system.

However, sensor based micro-scale energy harvesting introduces new challenges due to the fundamental fact that the output power from a sensor is time varying and often minuscule. Unfortunately, current energy harvesting solutions are not applicable because they are designed to meet specific performance requirements, such as high voltage gain \cite{7, 8}, high drive capability \cite{9}, and high efficiency \cite{10}. This paper proposes a complete energy harvesting solution that includes both an energy harvester that works with an extremely small power source (\textit{e.g.}, a sensor) and a batteryless target system powered solely by the harvester. We prove the concept by implementing a board level prototype \textit{SEnergy} using only off-the-shelf components and a photodiode sensor (Figure 1). Specifically, this paper makes the following contributions:

- We propose an exponential topology charge pump architecture that works with an ultra-low capacity power source that has an output voltage as low as 330mV. We use the charge pump to design a system powered by a sensor.
- We present \textit{SEnergy}, a board level prototype of the proposed energy harvester architecture and a 2.4GHz wireless connectivity equipped target system using off-the-shelf components. A photodiode is multiplexed to function as a sensor and as an energy source when it is idle.
- We demonstrate the utility of \textit{SEnergy} by implementing and evaluating a wireless sensing application that adaptively transmits timestamped sensor data.
- To the best of our knowledge, this is the first design that proposes a complete self-powered batteryless solution in which the entire system is built only with off-the-shelf components and is powered by a sensor.
The remainder of this paper is organized as follows. Section II discusses the charge pump architecture proposed and used in our energy harvesting solution. Section III and IV present hardware and software architecture of the energy harvester and accompanying target system, respectively. Section V describes a rigorous evaluation that we performed on SENERGY with various usage scenarios demonstrating the utility and capability. Section VI describes related work and Section VII concludes the paper.

II. Charge Pump Architecture

The output voltage of a passive sensor is time-varying as it depends on the physical phenomenon being sensed (e.g., light intensity). Additionally, the output voltage is low, often in the range of a few hundreds of millivolts. Hence, before the output energy can be utilized, the voltage should be boosted to a normal operating voltage. A charge pump (CP) [11] is a voltage converter that is used to create a higher or lower (in case of negative polarity) voltage by employing a network of capacitors interconnected with switching devices (such as MOSFETs and diodes). Depending on the charge pump architecture, two or more non-overlapping clock signals control the switching devices so as to efficiently share charge among the capacitors. Compared to inductive voltage converters such as Boost or Flyback converters, which require inductors or transformers, charge pumps are preferred for energy harvesting applications due to the fact that the switched-capacitor circuits are well suited for IC integration. In this section, we explain the proposed charge pump architecture and evaluate its functionality.

A. Limitations of Existing Charge Pump Architecture

Over the past decade, several CP architectures (discussed in Section VI) have been proposed that operate at low input voltages. However, implementing these architectures at the board-level presents a major challenge as most CP architectures are designed for IC integration and often make greedy assumptions such as zero-loss in switches to simplify their analysis. Furthermore, they typically incur a large power overhead to generate the control clocks and leave an insufficient amount to power the target system. Therefore, we propose a custom exponential CP architecture that is controlled by a sub-threshold clock generator whose power consumption is in nanowatts and implement it at board-level.

B. Proposed Charge Pump Architecture

Figure 2 shows a voltage boosting circuit, henceforth referred to as a Complex Voltage Doubling Block (CVDB), of the proposed exponential CP architecture and illustrates its basic operations. A CVDB (Figure 2(a)) is a generic voltage doubler that can be utilized as the basic block of any CP architecture. A CVDB consists of two input ports and one output port. Every successive half clock period, the block transforms from a parallel configuration of capacitors to a series configuration and vice-versa by using two non-overlapping clocks (generation of the clocks will be discussed in Section II-D). As shown in Figure 2(b), during the first half of a clock period ($\phi_1 = H$), the capacitors are connected in parallel and $C_1$ and $C_2$ get charged to $V_{IN}$. Figure 2(c) shows the second half of the clock period ($\phi_1 = L$), wherein the capacitors are connected in series thereby summing up the voltages $V_C$, and $V_C$. Thus, the output voltage gets boosted to $2V_{IN}$ in the steady state.

Since the doubling is accomplished by the MOSFET switch $M_1$, its gate voltage ($V_G$) should be at least $V_C + V_{GS(th)}$ to effectively transfer charge between the top plate of $C_1$ and the bottom plate of $C_2$. In other words, $M_1$ requires a gate voltage greater than that of the power source. In order to address this issue, the interconnecting MOSFET switch $M_1$ acquires the required gate voltage from a static load resistive inverter ($R_{LF}$). Thus, the magnitude of the back-gating voltage is always sufficient to completely turn on $M_1$ if the voltage level of the input ports are identical and $V_{GS(th)}$ is less than or equal to $V_{IN}$.

A diode ($D_1$) is placed right before the output port to block reverse current. The reason for choosing a diode over a MOSFET switch is that it simplifies the overall CP architecture. Consequently, a load capacitor connected to the output port can be charged up to $2V_{IN} - V_F$, where $V_{IN}$ is input voltage and $V_F$ is forward voltage drop of the diode.

C. Example of Two-stage Configuration

Consider the two-stage CP configuration as shown in Figure 3. It consists of two CVDBs and a Fundamental Voltage Doubling Block (FVDB) whose architecture and operation is identical to a CVDB albeit without a back-gating inverter. The FVDB shares the inverter output, $\bar{\phi}$, with the CVDB of the same stage to avoid additional power dissipation. Thus, each stage requires only one CVDB and the remaining voltage doublers can be configured using FVDBs.

The output voltage $2V_{IN} - V_F$, generated by CVDB and FVDB in the first stage, is fed into another CVDB in the second stage. The second stage CVDB produces $4V_{IN} - 3V_F$ and, thus, accomplishes exponential voltage boosting. The output voltage of a particular stage can be expressed using equation (1), where $N$ denotes the stage number, $V_{IN}$ is the input voltage, and $V_F$ is the forward voltage drop of a diode.

$$V_{out} = 2^N(V_{IN} - V_F) + V_F \quad (1)$$

The blocks of each stage alternate between series and parallel formation for the capacitors. Hence, while the capacitors in the voltage doubling blocks of the first stage are in series configuration, the capacitors of the CVDB in the second stage are in parallel configuration to acquire the energy available at its input ports. During the following half clock period, the CVDB in the second stage doubles the voltage of its capacitors and transfers it to the subsequent stage. In other words, the capacitors in the voltage doubling blocks are working as intermediate energy storage elements. Considering the minuscule amount of power available from the power source (sensor), this is one of the most important architectural features contributing to the overall success of the proposed exponential CP architecture.

D. Control Unit Design - Clock generator

The CP architecture requires a control unit that generates two non-overlapping clocks that are used to alternate
Fig. 2: Complex voltage doubling block (CVDB) of the proposed CP architecture and its operation

between series and parallel configurations. The control unit is an essential component of all CP architectures. However, its power consumption presents a huge overhead to the system and often renders a CP infeasible or impractical to use. For example, the control unit in a Dickson CP [12] has to be driven with a high amount of current to prevent the clock used for voltage doubling from collapsing. To address this problem, we designed an ultra-low power control unit consisting of a sub-threshold nanowatt RC oscillator that is followed by a clock magnitude amplifier. Figure 4 shows the architecture of the control unit.

The nanowatt power consumption is obtained by exploiting the sub-threshold characteristic of N-channel enhancement MOSFETs. A MOSFET is in sub-threshold mode if the gate to source voltage, \( V_{GS} \), is lower than its threshold voltage \( V_{GS(TH)} \). In this mode, since the current flowing through the MOSFET is negligibly small, it is usually regarded as turned off in most applications. However, a small amount of current still flows through and an exponential relationship with \( V_{GS} \) is observed. Therefore, even in the sub-threshold mode, we have control over the drain to source current \( I_{DS} \).

For example, if we use ALD110904 (\( V_{GS(TH)} = 0.4 \text{V} \)) from Advanced Linear Devices (ALD), the RC oscillator can operate down to \( 0.14 \text{V} \) as indicated in the device application note [13]. The frequency of the clock generator is generally determined by \( f_{OSC} = \frac{1}{2\pi R_3 C_{OSC}} \). The charging of \( C_{OSC} \) is limited by \( R_3 + R_4 \) and the discharging of \( C_{OSC} \) is limited by the current drive of \( M_3 \). Once the circuit starts oscillating, two non-overlapping clocks are produced using the output buffer amplifiers \( M_4 \) and \( M_5 \). Subsequently, the clock magnitude amplifier increases the magnitude of the clocks to a predefined level. The clock magnitude amplifier is identical to the proposed CP architecture (discussed in Section II-B), except that it has a linear topology. The amplifier can increase the magnitude of the clock signals by including additional intermediate stages.

III. SENERGY ENERGY HARVESTER BOARD

SENERGY’s primary design objective is to multiplex the functionality of the on-board sensor as both a sensing element and a power source. To achieve this, we designed an energy harvester board (EHB) for SENERGY, which is able to harvest energy from the sensor and supply power to the target system. Figures 5(a) and 5(b) depict the hardware block diagram and our implementation of the EHB, respectively.

A. Hardware Architecture

The hardware architecture of the EHB consists of four blocks, as shown in Figure 5(a). The sensor branching block diverts the voltage that it receives from the sensor to the control unit for clock generation, to the charge pumps for energy harvesting, and to the target system for data collection. The energy harvesting block consists of two identical charge pumps operated on opposite phases of the clock. Two CPs operated in this manner maximize the utilization of the sensor output for energy harvesting. Therefore, when one CP is in the charging phase, the other CP is in the voltage boosting phase. The two non-overlapping clocks are produced by the control unit. Finally, the output of the charge pumps are stored on two different capacitors \( C_{STOR1} \) and \( C_{STOR2} \). Both the outputs are made available to a target system that can make use of them as required.

B. Hardware Implementation

We choose a photodiode S1133-01 from Hamamatsu Photonics as the sensor for the EHB. The short-circuit current for a photodiode varies linearly with the intensity of incident light. From measurements, the S1133-01 used for our experiments gives a short-circuit current \( I_{SC} \) of 2.1\,\mu\text{A} under 100\,lx. The open circuit voltage, \( V_{OC} \), is typically 430\,mV in the office and
600 mV when outdoor on a cloudy day. Since the photodiode acts as a current source, the output voltage reduces with an increase in current draw. Therefore, the EHB is designed to operate for \( V_{IN} \geq 330 \text{ mV} \).

The sensor branching block’s task is to divert the sensor output to the energy harvester and the target system. Usually, the energy harvesting takes place when the sensor is idle. However, for some sensors such as a photodiode, such a mutually exclusive operation might not be necessary. EHB’s design allows the sensor measurement to be made even when the CPs are active. This is achieved by using a 1 \( \Omega \) shunt resistor that is placed in series with the CPs. As shown in Figure 6, the sensor output is used for harvesting and the voltage across the resistor is used to perform a sensor reading.

For energy harvesting, we implemented a pair of the proposed four-stage exponential CPs. The organization of the voltage doubling blocks and the associated output voltage levels are shown in Figure 7. Equation (1) highlights the importance of minimizing diode loss in our CP implementation. The diode loss accumulates exponentially with the number of stages and hence degrades the output voltage considerably. Therefore, the loss has to be minimized by selecting a diode with ultra-low forward voltage drop. Hence, we use a Schottky Barrier diode\(^1\) that has a forward voltage drop of 100 mV for tens of \( \mu \text{A} \) of current. Additionally, the EHB employs low-threshold (0.2V and 0.4V) MOSFETs\(^2\) in the charge pump and control unit to achieve efficient switching in the presence of low input voltages.

The energy being harvested is stored in the storage capacitors \( C_{STOR1} \) and \( C_{STOR2} \), which are connected to the last stage of each CP. The capacitor sizes are configurable and vary based on the application. Finally, the two capacitors may be configured to be in parallel by the target system so as to act

\(^{1}\) NSR0240P2T5G from On-Semiconductor  
\(^{2}\) N-channel enhancement mode MOSFET ALD110904 \((V_{GS(TH)}=0.4\text{V})\) and ALD110902 \((V_{GS(TH)}=0.2\text{V})\) from ALD
C. Evaluation

Figure 8 shows the result of an experiment where we varied the light intensity incident on the sensor from an ordinary household bulb and observed the input current, input voltage, and output voltage of the CP. In the experiment, the two outputs of the CPs are merged and supplied to a 1 μF capacitor. The CP begins to boost input voltages from 330mV. This is because the EHB design is optimized for indoor light intensity of around 450lx, which gives open circuit voltage, \( V_{OC} \), of 430mV. Based on the fractional open-circuit voltage method, introduced as one of the maximum power point tracking methods (MPPT) in [15], the minimum operating voltage is carefully chosen as the 76% of the open circuit voltage, i.e. 330mV.

\[
\begin{align*}
V_{IN-VF} & \sim 2V_{IN-VF} \\
4V_{IN-VF} & \sim 4V_{IN-VF} \\
8V_{IN-VF} & \sim 8V_{IN-VF} \\
16V_{IN-VF} & \sim 16V_{IN-VF}
\end{align*}
\]

The power overhead for voltage conversion at 330mV is 7 μW. We can significantly reduce the power consumption if the resistive inverters are replaced with other types of ultra-low power, low threshold voltage inverters (e.g., CMOS inverter). Unfortunately, such inverters are not available as off-the-shelf components. However, the power dissipation of the resistive MOSFET inverters is minimized by employing the asymmetric blocks, CVDB and FVDB, that share an inverter per stage.
below the threshold voltage of $SVS_{off}$. Then, the load switch will open if the energy stored in $C_{STOR}$ is depleted or the buffer is turned off by asserting its enable signal upon the completion of a given task.

Additionally, once the TB is powered on, it can redistribute the energy stored in the final capacitors from one to the other by using a CRS. The CRS is a switch that bridges the current path between $C_{STOR1}$ and $C_{STOR2}$. The charge redistribution mechanism enables flexible reconfiguration of the final capacitors by introducing a channel for energy exchange. The use of the CRS will be discussed in Section V-A with an example scenario.

As a sensor device, TB should support accurate measurement of the sensor data. For that purpose, a sensor interface unit, shown in the Figure 6, amplifies the small voltage that appears across the shunt resistor of the EHB by using an operational amplifier that has a voltage gain of 200. With the 12-bit ADC and 1.15 volt internal band-gap voltage reference of the CC2530 MCU on the TB, it is possible to measure up to around 273,800 lx with a resolution of 133 lx.

![Hardware block diagram of the target board](image1.png)

(a) Hardware block diagram of the target board

![Image of the target board](image2.png)

(b) Image of the target board

**Fig. 9: Senergy target board**

### IV. Senergy Target Board - A Wireless Sensor Node

#### A. Hardware Architecture and Implementation

In order to demonstrate the viability of using the EHB as a power source, we developed a custom target board (TB) that is to be powered from the EHB. The TB is a wireless sensor node that communicates over the 2.4GHz ISM band using an RF SoC CC2530 module from Texas Instruments. Figures 9(a) and 9(b) show the hardware block diagram and our implementation of the TB respectively. In addition to the communication module, it also consists of a power management unit, a sensor interface unit, an RTC IC, and a USB-to-serial interface.

The power management unit (PMU) controls the current path between the EHB and TB. Specifically, the PMU consists of a charge redirection switch (CRS) and two power gating circuits (PGCs), one for each CP. For efficient energy harvesting and to reduce charge leakage, it is important to isolate the TB from the output capacitor of the EHB, $C_{STOR}$, until a sufficient amount of energy has been accumulated in it.

The PMU seeks to address the issue by using a PGC (Figure 10) that performs the isolation and consumes only 160 nA. The PGC includes a supply voltage supervisor (SVS), a load switch, and a buffer. The functioning of the PGC is described below. The SVS constantly monitors the voltage at $C_{STOR}$ and releases the active-low reset pin once the voltage reaches the predefined threshold voltage level, upon which the load switch closes. However, $C_{STOR}$ starts discharging immediately and the voltage falls below the $SVS_{off}$ threshold. Consequently, under normal circumstances, the SVS will immediately assert the reset pin and the load switch will open. In order to prevent such an immediate shutdown, a buffer with a very short propagation delay (5.3 ns) is placed between the SVS and the load switch. The function of the buffer is to hold the load switch enable signal before the SVS turns off. As a result, the load switch remains closed even if the voltage level of $C_{STOR}$ goes down.

For maintaining a notion of time, the TB is also equipped with an RTC IC that consumes only around 100 nanowatts of power. In addition, for RTC time synchronization, the TB also has a USB-to-serial interface. Before deployment, the RTC time can be synchronized with the wall-clock time through this interface. While the TB is plugged into the USB interface, it is also possible to charge the final capacitors using USB port power.

#### V. Experimental Evaluation

We evaluated the Senergy platform using a set of experiments and usage scenarios. We demonstrate two use cases where the TB accomplishes a given task by using the energy harvested from the sensor. The first experiment demonstrates how sensor data can be transmitted to a base station during the day using the sensor powered Senergy board. To implement this, we suggest an adaptive algorithm that enables perpetual operation. The second scenario demonstrates how the proposed sensor-powered solution can be used to enable continuous operation of an RTC module.

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5 CC2530 RF module is not shown 6 TPS3839L30 from TI 7 AP2281 from Diodes 8 SN74AUP1G57 from TI 9 ADA4051 from Analog Device 10 PCF2123 from NXP 11 CP2102 from Silicon Labs
A. Adaptive Sensing

In this application scenario, we demonstrate how Senergy enables sampling and transmitting of RTC-timestamped sensor data while being powered by the sensor itself.

Algorithm 1: Sense and Transmit Evaluation Application

**Input:**
- \( V_{TH1} \): Minimum voltage required to execute given application
- \( V_{TH2} \): Critical RTC voltage
- \( L_{TH1} \): Minimum light level required for EHB to harvest energy

**Procedure:**

1. while TB is powered do
2. \( \text{if} \) USB is connected then
3. Charge \( C_{TB} \) and \( C_{RTC} \);
4. Synchronize RTC with wall-clock time;
5. \( \text{else} \)
6. \( \text{if} \) RTC time is synchronized then
7. \( s \leftarrow \) getLightSensorData();
8. \( t \leftarrow \) getRTCtime();
9. Timestamp the sensor data;
10. \( \text{if} \) \( s \geq L_{TH1} \) then
11. \( \text{if} \) Sleep timer is not initialized or expired then
12. \( V_{CTB} = \) getVoltageOfCTB();
13. \( \text{end if} \)
14. \( \text{if} \) \( V_{CTB} \geq V_{TH1} \) then
15. \( V_{CRTC} = \) getVoltageOfCRTC();
16. \( \text{else} \)
17. Enqueue the sensor data;
18. Redirect charge from \( C_{TB} \) to \( C_{RTC} \);
19. \( \text{end if} \)
20. \( \text{else} \)
21. Construct a packet;
22. Transmit the packet;
23. \( \text{end if} \)
24. \( \text{end if} \)
25. \( \text{else} \)
26. Enter extended sleep mode;
27. \( \text{end if} \)
28. \( \text{else} \)
29. Enqueue the sensor data;
30. Enter extended sleep mode;
31. \( \text{end if} \)
32. \( \text{end if} \)
33. \( \text{end while} \)

Algorithm 1 describes our evaluation application for Senergy wherein the sensor data is transmitted when sufficient energy has been harvested. We define \( C_{TB} \) as the capacitor that supplies power from the EHB to the target system, and \( C_{RTC} \) as the dedicated power source of the RTC sub-system. Before deployment, Senergy synchronizes the on-board RTC via a USB. During this time, the storage capacitors of the EHB are fully charged. Thus, Senergy avoids the initial charging overhead of the capacitors. Once the system is deployed and powered via the EHB, it proceeds to execute the application tasks. First, a predefined flag is checked to verify whether the RTC time has been synchronized. As soon as this is confirmed, the application samples the sensor data. By comparing the sensor data with a predefined threshold light intensity, the TB makes a decision to transmit the data or to enter an extended sleep mode. Senergy has two sleep modes, namely, normal sleep mode (NSM) and extended sleep mode (ESM). ESM facilitates the EHB to harvest sufficient energy in the presence of constrained light intensity, whereas NSM reduces the power consumption between successive transmissions. The energy consumption of each application task executed on the TB is characterized before deployment. If Senergy transmits the data when it receives insufficient light intensity, it will use up the energy that may otherwise be used to keep the system in ESM. Therefore, on receiving less intensity light, a pessimistic approach is adopted wherein the system enters ESM after enqueuing the sampled data.

On the other hand, if the measured light intensity is deemed sufficient, the energy remaining in \( C_{TB} \) is measured. If the voltage of \( C_{TB} \) is less than that required for performing a successful transmission, the system allows it to recharge by entering ESM. Finally, the energy remaining in \( C_{RTC} \), the capacitor supporting the RTC module, is measured. In the event that the remaining energy is less than the energy required for maintaining RTC time, the sensor data is enqueued into a circular buffer, and the charge from \( C_{TB} \) is redirected to \( C_{RTC} \) using the CRS. Then, the system enters NSM. Otherwise, Senergy transmits a packet with the timestamped sensor data before entering NSM.

Figure 11 shows the result of an experiment conducted in an outdoor environment. The experimental setup and test conditions are described below. The output of the CPs is tied up and supplied to the 330uF capacitor. The RTC IC on the TB is configured to be powered by a 30mF ultra-capacitor\(^\text{12}\). The ultra-capacitor is fully charged before deployment using USB port power when the TB is connected to a PC via USB for time synchronization. The TB can be powered whenever the voltage level of the 330uF final capacitor attains 2.66V, which is the predefined threshold voltage level of the SVS in the PMU. A base station is placed at a distance of 10 m to receive packets from Senergy. Additionally, the experiment was planned and conducted on a day with varying weather conditions. In fact, on the day of experiment, the weather condition was radically changing and it started by being sunny with clear skies and transitioned to a cloudy overcast weather as the day progressed. Moreover, in the course of the experiment, there was light rain intermittently.

Figure 11 indicates the light intensity, and the number of packets received at the base station for every 15 minutes. In addition to that, the weather condition for every hour is shown above the graph (taken from The Weather Channel\(^\text{13}\)). As shown in the figure, the number of packets received depends on the light intensity, except at the beginning of the experiment. This is because the 330uF capacitor is initially discharged and therefore, energy is spent in charging it up. During the experiment, a total of 188 packets were received and the average interval between each packet was 1 minute and 40 seconds. Therefore, Senergy can be used for any light intensity sensing application that has sensing interval longer

\(^{12}\) PAS311HR-V A6R from Taiyo Yuden \(^{13}\) The experiment was conducted on Apr 24, 2014 in West Lafayette, IN, USA
than the average charging time. Considering the fact that such applications are heavily duty cycled and that outdoor light intensity changes relatively slowly, the minimum interval that SENERGY supports can easily meet the operation requirement of most applications.

Fig. 11: Successful transmissions vs. Time of day

B. Perpetually Powered Sub-system

A real-time clock (RTC) is a critical component in an embedded system that enables correlation of its internal activities with the external world. Other than time keeping, RTC performs several other functions such as synchronization, alarms, and periodic interrupts. Therefore, it is imperative that the RTC sub-system have an uninterrupted power supply. SENERGY’s sensor powered solution addresses this issue and enables perpetual operation for the RTC module. Due to the extreme low power consumption of a typical RTC IC, the EHB is capable of supplying the required power even in challenging environments. For instance, the RTC IC used in this paper can operate down to 1.1 V with current consumption of 100 nA. We confirmed the perpetual operation of RTC experimentally.

In the preceding scenario, we confirmed that SENERGY can transmit a total of 188 packets per 315 min under mostly cloudy weather condition. As shown in Figure 12, the TB consumes 0.02 μAh of energy at 2.66 V for 6.25 ms. About half of the energy is consumed for sampling the sensor and the other half is used for transmission. Given the fact that each sense and transmit operation consumes 0.02 μAh, we compute the total energy harvested by the EHB to be 3.76 μAh. This is equivalent to the amount of energy required to operate the RTC IC for 37.6 hours. The analysis concludes that the harvested amount of energy is more than enough to operate the RTC IC overnight.

VI. RELATED WORK

A. Self Powered Systems

Self-powered sensor systems, which rely on some form of energy harvesting or energy scavenging, are widely prevalent [16]–[20]. Often, such systems are constructed with a dedicated energy harvesting component (like a solar cell, piezoelectric element, thermoelectric generator, etc.), and an independent sensor. The primary focus of research in such systems has been to optimize the energy harvesting circuitry [21], [22] or to optimize the sensor itself [23]. For example, Tsui et al. [24] fabricate and demonstrate a computational module with a dedicated energy harvesting component to power the system with input voltages as low as 190mV. The sensing circuit, in this case, is independent of the energy harvester. In addition, a thorough analysis and discussion of the various trade-offs present in such a design are not discussed. Comparatively, SENERGY proposes to scavenge the energy output from the sensor during idle time and use it as an energy source for the system during active state. In [25], [26], self-powered sensor systems are described wherein the sensor output is multiplexed as a power source. Pan et al. [25] simulate a system powered intermittently by low level vibrations of a piezoelectric element that is also used as a sensor. However, the simulations do not account for the RC losses involved in a real deployment and tend to an ideal case. On the other hand, [26] demonstrates a self-powered inertia sensor but does not analyze a system where the sensor is used as the power source. Our paper demonstrates SENERGY, a wireless embedded system that is integrated with a photodiode, which functions as a light sensor in active state, and as a power source in idle state. We quantify our results and discuss the trade-offs involved in designing such a perpetual system.

B. Charge Pump Architectures

In energy harvesters, utilizing charge pumps for boosting the input voltage is a well known technique. There has been sufficient interest in the research community for optimizing the efficiency of charge pumps [27]–[29]. Charge pump architectures can be broadly classified into Dickson, Fibonacci, and exponential. In a Dickson charge pump [30], the voltage gets boosted linearly with each successive stage. In contrast, the Fibonacci and exponential architectures are non-linear architectures. Voltage gets incremented as a Fibonacci sequence across stages in the Fibonacci architecture [31], while voltage is boosted exponentially with each subsequent stage in an exponential charge pump architecture [29], [32]. SENERGY borrows concepts from all the three architectures but is most closest to the exponential architecture. A Dickson charge pump multiplies the voltage by transferring charge across symmetric stages separated by diodes [30], [33], [34]. Diodes are implemented to isolate each stage, and to prevent any back-flow of charge. Implementing diodes minimizes the control logic required for the architecture. However, the associated voltage drop with diodes decreases the multiplication efficiency of the charge pump. For example, in a charge pump architecture that employs MOSFET-based diodes, the diode drop can be attributed to the $V_{th}$ of the FET. On the other hand, charge
transfer switches (CTS) use MOSFETs that are statically controlled by the output voltages of forward stages for toggling the MOSFET switch ON and OFF [35]. By implementing a feedback control, the gate-source voltage of the MOSFET is increased, and therefore the lower voltage output of a stage can be equal to the highest voltage at the input. Wu et al. [36] improves the efficiency of the CTS-based architecture by introducing dynamic feedback control from succeeding stages. Our charge pump architecture in \textsc{Senergy} utilizes diodes as well as dynamic CTS to optimize the voltage efficiency and minimize the control circuitry power dissipation.

Common charge pump architectures employ two non-overlapping clocks for operation. Therefore, two charge-pumps could be operated in parallel with inverted control logic and this ensures a continuous charge transfer to the output stage capacitor [37]. \textsc{Senergy} also follows the same principle to maximize the energy harvesting time. Conventional exponential charge pump circuits are symmetric in nature [29]. The architecture is designed such that a fundamental block is repeated in each stage. \textsc{Senergy}, even though it is an exponential charge pump in nature, has a custom charge-pump architecture utilizing sub-threshold MOS-characteristics to achieve the desired output. The charge pump architecture consists of multiple distinct fundamental blocks, which make up the different stages of the architecture. Our approach adopts the strengths of all the previous architectures to optimize for conversion efficiency in the presence of nonidealities.

VII. CONCLUSIONS

In this paper, we presented a novel embedded systems architecture that utilizes a sensor as both a sensing element and a power source. We also demonstrated the entire design flow that spans from energy harvesting to utilization of the harvested energy. As a proof of concept, we designed and implemented \textsc{Senergy}, a batteryless wireless sensing platform that is powered by a photodiode sensor.

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