Power Solutions of A Vibration-Powered Sensor Node

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***Abstract*—Vibration energy harvesting (VEH) technology enables the Internet of Things (IoT) devices and applications to be deployed at any place, where mechanical vibrations or motions are available. Given the intermittent, stochastic, or impulsive features of many ambient vibration sources, the VEH-based IoT systems must have a reliable energy management unit (EMU), carefully dealing with energy fluctuation and uncertainty. The cyber part of these systems should also schedule tasks by taking a substantial consideration of the source features. Emerging energy-aware state checkpointing technique enables fault-tolerant computations and lets the program survive longer under energy fluctuation or shortage. This paper focuses on the power solutions of energy-aware VEH-based IoT systems. Three possible power solutions are discussed in detail. The most fundamental one is based on an off-the-shelf dc-dc converter with fixed-threshold under-voltage lockout (UVLO). The second one adds an energy-level indicator as a passive interrupt for better realizing the energy-aware computing tasks. The third one uses the on-chip analog-to-digital converter (ADC) to carry out active polling for estimating the energy level in the storage capacitor. Both the second and third designs can reinforce the energy-awareness of the VEH based IoT systems towards a more robust operation. The system performances using these power conditionings under intermittent vibration excitation are experimentally studied based on a vibration-powered IoT platform. The energy overheads of the fundamental regulator module and additional interrupt or polling types of energy storage monitoring are also quantified. Useful comments are drawn based on this comparative study. They help VEH system designers to better select a suitable solution for realizing the specific IoT design targets.**

***Index Terms*—Power solution, vibration energy harvesting, power management circuit, intermittent computing**

I. Introduction

In recent years, technological advances on small and low-power computing devices have been witnessed across various application domains, including Internet of Things (IoT) devices, wearable, implantable, and ingestible medical sensors, infrastructure monitors, and small satellites [1]. The energy harvesting technology enables several low-power applications to be powered by using the energy scavenged from their ambiance. It liberates the IoT devices from power cable restriction or frequent battery recharging. [2]. Among various energy harvesting technologies, vibration energy harvesting (VEH) has caught much research interest, due to the abundance of explorable vibration in our surroundings [3]–[5]. Compared with sensors powered by solar or radio frequency (RF) wave, the deployment of vibration-powered sensors is not limited by illumination or RF signal intensity [6], [7]. It can be installed at any place, where vibrations or mechanical movements exist. For example, the vibration-powered sensors can be deployed in large infrastructures, which undergo vibrations, or other moving objects such as vehicles, human, or animal bodies.

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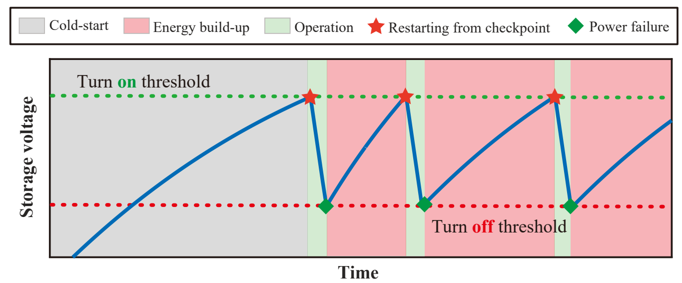

Fig. 1. Intermittent execution of VEH-powered IoT systems. Energy availability depends on environmental conditions and computing behavior. Intermittent execution is a side-effect of this battery-free model, with outages of the unknown length separating bursts of execution.

However, the features of different sources have a lot to do with the energy harvester design and optimization. There are several challenges for implementing the vibration-powered IoT systems. First, the source dynamics of VEH are more complicated than those of its solar and RF counterparts. Holistic design requires substantial idea exchange with dynamicists. Furthermore, ambient vibrations are usually broadband. Some vibrations occur in intermittent mode, while some others might work in transient mode. The diversified features of different vibration sources make it difficult to standardize or generalize the mechanical harvester designs. Customization is necessary for meeting the vibration feature of a specific application. In general, unlike traditional machines using cord power or batteries, the devices powered by VEH or other harvesting technologies usually operate in *intermittent* mode. Because of the intermittent feature of some vibration sources, energy is not always available. Even when energy is available, it takes time to buffer sufficient energy for carrying out specific computational functions [8]. In intermittent operation, a full task is carried out with interleaving computations and unpredictable energy build-up processes [9].

Emerging *energy-aware state checkpointing* software system [10]–[15] enables long-running computations and lets the program survive after periods of energy unavailability. The intermittent computing model is shown in Fig. 1. When the power outage is imminent, a snapshot of the system states, such as processor registers and SRAM data, are saved in the non-volatile memory, such as Flash, Ferroelectric RAM, and Magnetoresistive RAM. In the next power burst, the system reboots. The system states are recovered from the stored checkpoint data, such that the program execution resumes. As a result, time-consuming programs execute progressively in small segments by looking at the energy availability [12]. On the other hand, checkpointing operation inevitably involves non-negligible execution time and energy overhead. If the buffered energy is less than the energy consumption required for saving and recovering checkpoints, these intermittent computing devices can hardly execute any program. Therefore, it is crucial to minimize the energy overhead of the checkpoint scheme and balance the energy income in energy harvesting and energy consumption in computing. The checkpoint scheme's key idea is that the microcontroller unit (MCU) should keep track of the buffered energy at run time and adjust its code execution pace accordingly. For example, an operating scheme called Mementos [10] uses an analog-to-digital (ADC) converter to quantify the storage voltage and make checkpoint decisions by comparing the measurement result to specific thresholds. Above the checkpoint voltage, Mementos assumes that it does not need to write a state checkpoint. When the storage voltage is below the threshold, it indicates that power failure is imminent, the checkpointing state must be saved immediately. Besides the ADC active polling solution, an analog comparator is also a popular solution for performing energy measurement. Different from the ADC solution, the comparator one relies on a passive interrupt routine.

This paper provides a comparative study on different energy-aware state checkpointing schemes for VEH systems. Considering the challenges mentioned above of VEH, additional energy monitoring mechanism is necessary for the robust operation under volatile vibration conditions. Under a simulated intermittent vibration excitation, we evaluate the energy cost and additional execution time of the state-of-the-art solutions on a vibration-powered IoT platform - ViPSN [16]. This study provides a valuable reference for the design of vibration-powered IoT systems.

II. Power Solutions

In a VEH-powered IoT system, the power management circuit plays an essential role in guaranteeing robust and reliable operation under complicated vibration conditions. It is responsible not only for providing temporary energy storage to extra harvested energy but also for supplying power at a constant voltage to digital users, such as CPU, sensors, RF modules. Many vibration sources are intermittent, fluctuating, and unpredictable. Therefore, vibration-powered devices should be able to operate in volatile vibration environments, even as extreme as intermittent or transient cases. Besides the complicated source conditions, the power management circuit should also maximize the harvested energy income from the supply side, minimize the energy dissipation in energy conversion, and properly deliver power under any loading demand. The checkpointing designs endow storage energy awareness to the digital system, such that necessary interactions between energy storage and software programs are able to be realized. In this section, we comparatively study three typical power solutions in detail.

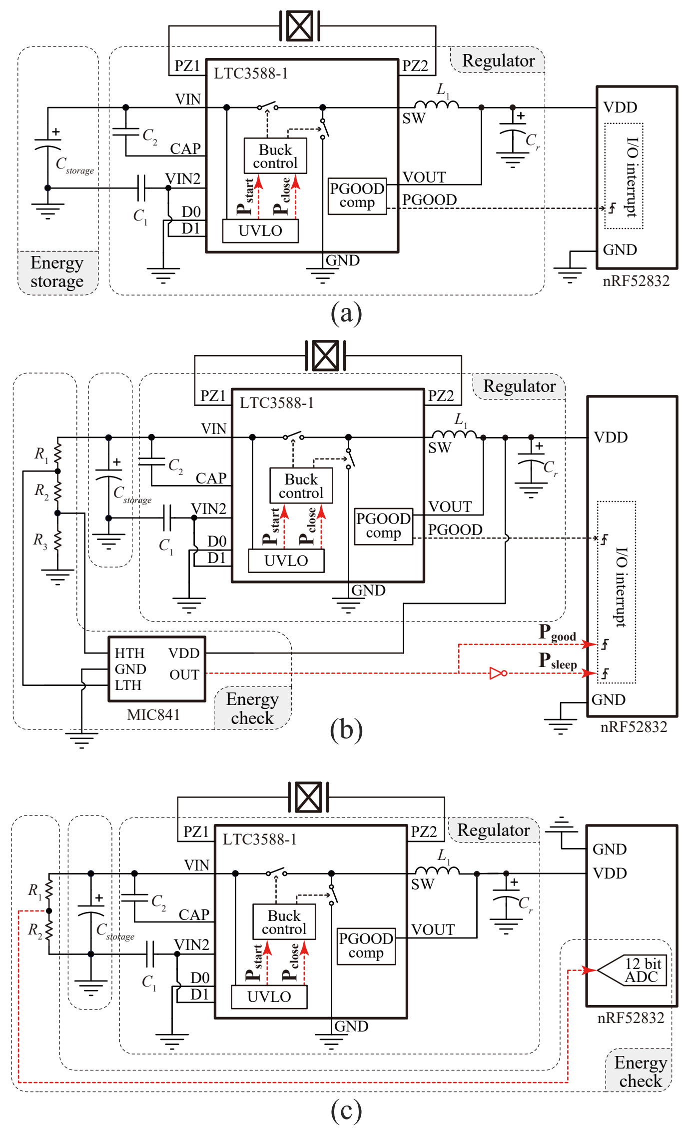

Fig. 2. Power solutions for VEH systems. (a) Fundamental scheme (dc-dc regulator with fixed-threshold UVLO) without energy-level indicating signal. (b) Energy checkpointing scheme using comparator interrupt. (c) Energy checkpointing scheme using ADC polling.

A. Fundamental Scheme without Checkpoint

The first studied solution is a dc-dc regulator with a fixed-threshold under-voltage lockout (UVLO). The most extensively used off-the-shelf integrated circuit (IC) chip LTC3588, which was developed by Linear Technology Co., provides such a fundamental solution [17]. LTC3588 can handle the input ac voltage in the range from 2.7 to 20 volts. It is specifically designed for piezoelectric VEH applications [18], [19], because piezoelectric transducers give relatively high voltage output. LTC3588 integrates a low-loss full-wave bridge rectifier and a high-efficiency buck converter for power conditioning. In LTC3588, the UVLO module has a fixed rising threshold of 5 V (LTC3588-1) or 16 V (LTC3588-2). It makes sure that the system comes alive after there is sufficient energy in the storage capacitor. Besides the UVLO in the storage end, LTC3588 also offers a power good signal (PGOOD) in the output end, which indicates the availability of stable output voltage. The configuration of the fundamental power conditioning scheme is shown in Fig. 2(a).

In this basic solution, a trade-off between larger energy storage and higher charging and responsive speed must be made by carefully selecting a suitable storage capacitance value. Too small storage capacitance cannot guarantee survival after initialization; too large takes a long time to wake up. For example, in the design of Trinity [18], a self-sustaining and self-contained indoor sensing system powered by airflow induced vibration, a 1.5 F ultra-capacitor is selected as the storage device to satisfy the power consumption of the load sensor. A 1.5 F capacitor is pretty large for a VEH system and takes much time to charge up. The available energy after the UVLO rising threshold is $\frac{1}{2}C_{\text{storage}}(V_{\text{Pstart}}^2 - V_{\text{Pclose}}^2)$, where V_{Pstart} and V_{Pclose} are the UVLO rising and falling thresholds. Besides the fixed UVLO thresholds, the PGOOD pin of LTC3588 offers further information on the output voltage stability.

The storage capacitor needs to satisfy (1), so that the system has enough energy to exit the cold-start phase and complete the most energy-consuming task.

$$C_{\text{storage}} \geq \frac{2\left[\int_{T_i} P_{\text{static}}(t)\mathrm{d}t + E_{\text{task},i}\right]}{\eta\,(V_{\text{Pstart}}^2 - V_{\text{Pclose}}^2)}. \tag{1}$$

In (1), C_{storage} indicates the value of the storage capacitance; P_{static} represents the static power consumption of the system; η is the average dc-dc energy conversion efficiency; $E_{\text{task},i}$ is the energy consumption of load tasks, including initialization, sensing, transmitting, and sleeping.

B. Comparator Interrupt Checkpoint Scheme

The second and third solutions are enhanced power management circuits with additional energy-level indicating signals. Such schemes were adopted in many applications [16], [20]. By setting these energy-level indicating signals, the EMU informs the energy user about the up-to-date storage condition to help it better operate under fluctuating or intermittent vibrations. The second and third solutions differ in the checkpoint triggering methods. The second one is triggered passively as an interrupt generated by a low-power analog comparator, which compares the storage voltage to a user-defined threshold. The third one uses an active polling method for determining the necessity of checkpoint actions.

The configuration of the passive comparator interrupt checkpoint scheme is shown in Fig. 2(b). An external comparator is responsible for generating the checkpoint interrupt when the storage voltage is above the threshold. Before the interrupt, the MCU is set in the deep-sleep mode in order to save energy and wait for the energy accumulation. In this checkpoint scheme, two additional energy-level indicating signals $\mathrm{P_{good}}$ and $\mathrm{P_{sleep}}$ are added beyond the two internal UVLO signals $\mathrm{P_{start}}$ and $\mathrm{P_{close}}$. The two additional energy indicating signals ensure that the energy builds up in a conscious way, rather than simply passively waiting for the start-up, as the fundamental solution does.

$\mathrm{P_{good}}$ comes with the rising edge of the comparator output. It indicates that the storage capacitor has gained sufficient energy to guarantee the execution of the most power-consuming atomic operation. $\mathrm{P_{sleep}}$ comes with the falling edge of the comparator output. It warns that the energy storage is in shortage. The MCU must take an emergent routine to save the critical data and then go to the ultra-low-power deep-sleep mode. By adjusting the resistor network of the comparator, developers can change the voltage thresholds for generating $\mathrm{P_{good}}$ and $\mathrm{P_{sleep}}$ to ensure proper operations under different excitation conditions and computing demands. There are two critical amounts of available energy in this solution. The first is $\frac{1}{2}C_{\text{storage}}(V_{\text{Pgood}}^2 - V_{\text{Psleep}}^2)$ the energy amount between the V_{Pgood} and V_{Psleep} thresholds. This amount of energy should be sufficient to meet the energy demand of the most energy-consuming operation among checkpoint resuming, sensing, wireless communication, etc. The other is $\frac{1}{2}C_{\text{storage}}(V_{\text{Psleep}}^2 - V_{\text{Pclose}}^2)$ the energy amount between V_{Psleep} and V_{Pclose} thresholds. It should be sufficient to guarantee the execution of a successful checkpointing operation, such as pushing the program counter, key registers, and other global variables into the non-volatile memory stack.

C. ADC Polling Checkpointing Scheme

The third solution is an active polling checkpoint scheme, which is realized by periodically sampling the storage voltage with an on-chip ADC. The configuration of this solution is shown in Fig. 2(c). Active polling is a popular energy-aware solution for intermittent computing systems because it can be realized based on existing hardware without design modification [10]–[12]. In this solution, MCU decides to run specific codes or not by comparing the periodically sampled results of the storage voltage to a user-defined threshold. If the storage voltage is above the threshold, it is not necessary to write a state checkpoint. When the storage voltage is below the threshold, it indicates that power failure is imminent, the system should begin to write a checkpoint.

ADC polling scheme has a higher resolution than the two-level comparator on storage voltage measurement; however, the energy overhead, which is proportional to the active sampling rate, might be considerable, compared with the passive solution. Therefore, the polling scheme should be carefully designed in a power-limited scenario. Some polling strategies were mentioned in the previous studies. For example, Mementos [10] inserts a sampling point in each circular lock or function call. For any polling strategy, the more frequent

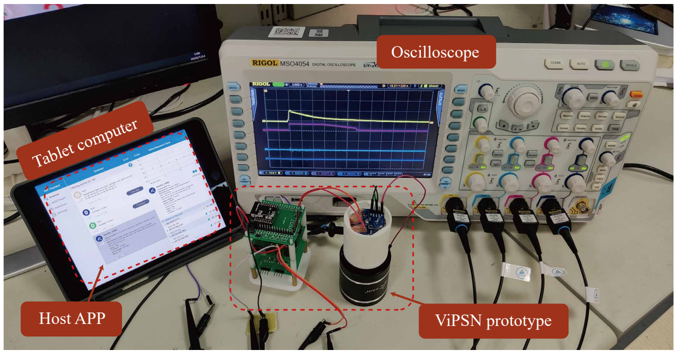

Fig. 3. Experimental setup. A tablet computer acts as the Bluetooth host to collect the beacon packets transmitted from a prototyped ViPSN.

TABLE I
POWER AND ENERGY STATISTICS.

Operation		**Energy (μJ)**	**Duration (ms)**
Initialization	DC-DC regulation	50.8	4.05
	Interrupt detection	50.9	4.06
	Polling check	51.09	4.10
Beacon broadcasting		61.77	4.71
ADC sampling		1.29	1.0

Operation			**Power consumption (μW)**
Sleeping			7.59
Static power	Regulator		5.0
	Interrupt detection		28.0
	Polling check	0.5 Hz	27.65
		4 Hz	32.16
		20 Hz	52.80

energy checks, the higher possibility the system can learn about rapid energy variation in runtime. Since many vibrations are intermittent, impulsive, or unpredictable, increasing the sampling rate inevitably produces larger energy overhead. Given an increase in the sampling rate for better energy-awareness, there is a critical point, where the measurement power consumption is the same as the harvested one. Above this critical sampling rate, the active polling scheme cannot sustain by making ends meet.

The static power consumption in this active polling scheme is summarized as follows:

$$P_{\text{static}}(t) = f_s E_{\text{adc}} + P_{\text{dc-dc}}(t) + P_{\text{leak}}(t), \tag{2}$$

where $P_{\text{dc-dc}}$ is the operating power of regulator; P_{leak} is leakage power, which is caused by the parallel leakage resistor of the storage capacitor; E_{adc} is the energy consumption of each ADC sampling; f_s is the polling sampling frequency.

III. EVALUATION

In this section, we evaluate and validate the three solutions on a VEH platform to provide guidance for the development of practical VEH systems.

A. Experimental setup

The experimental validation of the three solutions is carried out with ViPSN [16], which is an open-source vibration-powered IoT platform[1]. This platform has a vibrator that can simulate real-world vibration. In this study, the vibration energy is harvested by a piezoelectric transducer. Fig. 2(a)-(c) shows the circuit schematics of the aforementioned three typical power solutions based on a basic regulator, regulator with passive interrupt, and with active polling. LTC3588-1 [17] is used for the voltage regulation purpose. It integrates a low-loss full-wave bridge rectifier and a high-efficiency buck converter. MIC841 [21], a micro-power precise voltage comparator with adjustable hysteresis, is responsible for detecting the energy level of the storage capacitor. A programmable Nordic nRF52832 Bluetooth low energy (BLE) SoC [22] serves as the MCU and wireless module. It also has an on-chip ADC supporting up to eight external analog input channels with 12-bit resolution. It can be operated in a continuous conversion mode with a programmable sampling rate.

A BLE beacon template is chosen to evaluate intermittent execution. This protocol enables sensors to broadcast short packets to nearby Bluetooth-enabled devices, such as smartphones, to provide location/context-aware IoT services and applications [23]. Fig. 3 shows the experimental setup. In this study, we set the beacon broadcast interval as 500 ms. A tablet computer is used as the Bluetooth host for collecting beacon packets transmitted from the ViPSN prototype.

[1]https://github.com/METAL-ShanghaiTech/ViPSN

B. Power consumption analysis

The power and energy statistics of different tasks are shown in Table I. Before performing regular application tasks, for both the power management circuit and the BLE node, the initialization phase is necessary. So the harvested energy must first satisfy the energy consumption of initialization. Table I lists the energy consumption of different functions in these three power solutions, respectively. Each item summarizes the gross effect of the corresponding circuit hardware and software programs, such as a dc-dc regulator, interrupt function realized by an analog comparator or ADC sampling, and BLE beacon.

For the power solution of interrupt detection, the static power consumption includes that of the comparator and dc-dc regulator. The polling check's static power consumption is related to the ADC sampling frequency, as summarized in (2). Fig. 4(c) shows the current waveform in a round of beacon broadcasting. As listed in Table I, it consumes about 61.77 μJ of energy.

To guarantee a task completion without energy outage, we have to accumulate enough energy in the storage capacitor and carry out the computational task in a burst, rather than completely rely on the input power. According to (1) and the requirements, in the three different power solutions, i.e., basic regulator, interrupt scheme, and polling scheme, the minimum storage capacitances are derived 16.76 μF, 7.59 μF and 7.74 μF respectively. Therefore, in this study, we choose a 10 μF electrolyte capacitor as the storage device for the latter two solutions.

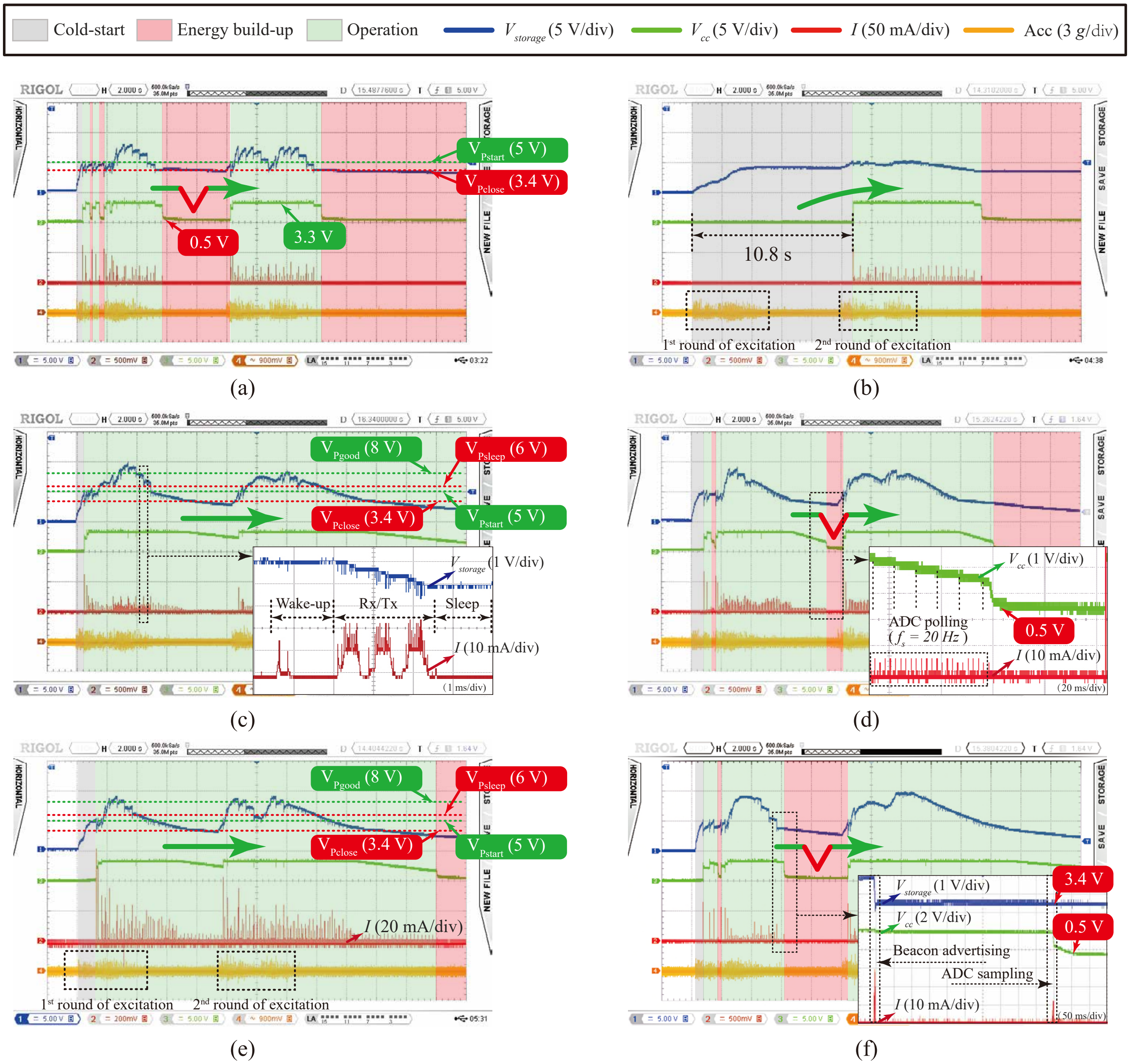

Fig. 4. The waveform of ViPSN prototype with three different power solutions, i.e., basic regulator (a and b), interrupt detection (c), and polling check (d - f). (a) Start-up with outage using small storage (10 μF). (b) Success but slow start-up without outage using large storage (100 μF). (c) Execution without outage using energy-indicating interrupt signals. (d) Startup with outage due to oversampling (f_s = 20 Hz). (e) Successful execution without outage using ADC polling check (f_s = 4 Hz). (f) Execution with outage due to under-sampling (f_s = 0.5 Hz). The frequency of the BLE beacon broadcasting is 2 Hz. (c) - (f) use small storage capacitor (10 μF). V_{Pstart} and V_{Pclose} are fixed thresholds, while V_{Pgood} and V_{Psleep} are tunable according to the most energy-consuming atomic operation.

C. Experimental validation

In the experiment, we use ViPSN to simulate the real-world vibration of a suspended bridge. The vibration data set is downloaded from the Energy Harvesting Network Data Repository[2]. The acceleration data used in this case is recorded from different locations at some suspension segments of the Clifton Suspension Bridge in the UK. When cars pass by a suspended segment of the bridge, significant vibrations are induced at some locations. We use the vibration data between 12 to 24 seconds, which was collected at the end of a suspended bridge segment and close to the pillars. Fig. 4 shows the vibration acceleration records (orange curve). It can be observed that there are two rounds of intensive excitation caused by passing cars.

[2]http://eh-network.org/data/

1) Intermittent execution: We compare the number of outages in ViPSN with the power solutions of a basic regulator, that with passive interrupt, and that with active polling schemes. The total number of outages for complete a specific work is regarded as a key index of efficient program execution. The more outages, the more energy is utilized for the checkpoint state saving and restoring, rather than useful computations. Reducing checkpointing operations before and after the outages allows an application to execute more efficiently under the same vibration excitation.

Fig. 4 shows the waveforms indicating the operational states of the ViPSN systems with the three power solutions. By only using a basic regulator, the outage is unpredictable; therefore, there is no state reference for controlling the pace of code execution. Because there is no energy-indicating signal, ViPSN cannot perform checkpointing operations, such as stopping the energy-consuming functions and entering the deep-sleep mode for saving energy. One can only increase the storage capacitance for eliminating the possible outage, which also depends on the incoming and consumed power. The available energy is determined by the fixed V_{Pstart} and V_{Pclose} thresholds. When the storage capacitance is small, say 10 μF, the system cannot start up without outage, which is highlighted by the red area in Fig. 4(a). It is possible to realize a successful startup by adopting a larger storage capacitance, for example, when C_{storage} increases from 10 μF to 100 μF, as shown in the green area in Fig. 4(b). Nevertheless, it requires a longer cold-start period, say, up to 10.8 seconds in this case.

By adding additional energy-indicating signals, the power solutions with checkpointing designs increase the available energy for code execution from $\frac{1}{2}C_{\text{storage}}(V_{\text{Pstart}}^2 - V_{\text{Pclose}}^2)$ to $\frac{1}{2}C_{\text{storage}}(V_{\text{Pgood}}^2 - V_{\text{Pclose}}^2)$. Such an amendment ensures that the stored energy is sufficient to meet the requirements of a start-up operation. Moreover, by learning about whether the storage voltage is between V_{Psleep} and V_{Pclose} thresholds, ViPSN can carry out the necessary checkpointing operation and effectively and robustly switches between full-speed computation and deep-sleep energy build-up phases. During an energy build-up phase, ViPSN remains in hibernation, but keeps some fundamental awareness, such that it can wake up at the following round of intensive vibration. The successful start-up process with the help of energy indicating signals is shown in Fig. 4(c).

By comparing the storage voltage (V_{storage}) with the software-defined thresholds, the power solution with a polling check can also provide two additional $\mathrm{P_{good}}$ and $\mathrm{P_{sleep}}$ energy indicating signals. When the rising edge of storage voltage crosses the threshold V_{Pgood}, ViPSN starts to broadcast beacon packets. On the other hand, When the falling edge of storage voltage crosses the checkpoint threshold V_{Psleep}, it indicates that power failure is imminent, and MCU should start the checkpointing operation. Fig. 4(e) shows a successful execution without outage between two rounds of intensive excitations.

2) Performance and energy overhead: Compared to the power solution with passive interrupt, timely awareness of the stored energy is determined by the ADC polling actions' sampling frequency. Fig. 4(d)-(f) show the performances of ViPSN with three different polling frequencies, say, 20 Hz, 4 Hz, and 0.5 Hz. For the 20 Hz case, the poling check's energy overhead is larger than the energy harvested from a vibration source during the same period; therefore, it is an over-sampling case. With the increase of static power consumption P_{static}, even if ViPSN captures the energy-warning signal $\mathrm{P_{sleep}}$, the amount of energy $\frac{1}{2}C_{\text{storage}}(V_{\text{Psleep}}^2 - V_{\text{Pclose}}^2)$ cannot satisfy the checkpoint function requirement. The system is unexpectedly shut down for a short period, as shown in Fig. 4(d). On the other hand, if the sampling rate is low, say 0.5 Hz, the state checkpoint might be missed. The system might also be shut down unexpectedly given the energy outage in such an under-sampling case, as shown in Fig. 4(f). In summary, the sampling frequency is quite sensitive for keeping a robust and reliable operation.

Although its sensitivity, the active polling scheme has another benefit for its flexible checkpoint threshold. Because ADC sampling provides a high resolution on the storage voltage, the software-defined threshold is in-situ adjustable. Therefore, it has a bigger potential to be applied in applications with more complex energy dynamics than other power solutions. By sophisticatedly carrying out some in-situ dynamic adjustments on the checkpointing threshold and sampling frequency of the polling actions, the polling scheme might work equally well as or even better than the passive interrupt scheme.

IV. Conclusion

The energy management unit plays an essential role in the VEH system towards robust and reliable operations. In this paper, we provide a comprehensive analysis of three possible power solutions for piezoelectric vibration energy harvesting (VEH) systems. These solutions include basic regulator, regulator with interrupt checkpointing scheme, and that with active polling scheme. They are validated and comparatively evaluated with experimental measurements based on an open-source hardware platform (ViPSN) towards standard IoT Bluetooth applications, e.g., BLE beacon. The objective is to highlight the importance of the checkpointing mechanisms towards energy-aware IoT systems. Without energy-awareness in operation, the basic version of the off-the-shelf regulator is likely to experience unexpected shut down during operation. Therefore, to carry out intermittent computing, which provides the feasibility of long-running computations and enables the program to cross periods of energy unavailability, the passive interrupt or active polling checkpointing scheme is necessary. In the experiment, via introducing additional voltage thresholds, which generates checkpoints, the passive interrupt solution enables robust start-up and program execution without any energy outage. In contrast, an active polling solution makes the tasks under a carefully designed sampling frequency. In future work, we will continue to investigate power solutions with adjustable or multilevel voltage thresholds, which makes a better synergy towards vibration powered intermittent computing systems.

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