ViPSN: A Vibration-Powered IoT Platform

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Abstract—In this paper, we introduce ViPSN (acronym of vibration-powered sensing node), a programmable Internet of Things (IoT) platform for the development of vibration- and motion-powered sensing and transmitting systems. It leverages the exploitation and utilization of ambient vibration energy by using a piezoelectric transducer. The roles and relations of six necessary modules, including energy generation unit (EGU), energy transduction unit (ETU), energy management unit (EMU), energy user unit (EUU), and edge demonstration unit (EDU) are discussed in details. In particular, an enhanced EMU is proposed by making necessary complements to an extensively used off-the-shelf integrated circuit (IC) solution for piezoelectric transducers. It provides more comprehensive energy storage indicating signals, such that the sensing, computing, and transmitting tasks can be carried out more robustly by keeping a good awareness of the remaining energy. Owing to the enhanced EMU design, vibration energy in various forms, such as intermittent and transient ones, can be more effectively harvested and utilized. The performance of ViPSN is evaluated, in terms of its lifetime and quality of service (QoS), under different vibration scenarios. The inclusive design and affiliated open-source project of ViPSN help build a new ecosystem for the research and development of vibration- or motion-powered IoT systems.

Index Terms—Kinetic energy harvesting, battery-free system, wireless sensor network, piezoelectric transducer, energy management.

I. INTRODUCTION

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VER the last decades, researchers have worked towards the realization of the Internet of Everything by deploying long-lasting, low-cost, environmental-friendly, and sustainable sensing nodes. They have continually redefined and refined this shared vision by creating new terms, such as “ubiquitous sensing”, “smart dust”, “TerraSwarm”, and the most recent “Internet of Things (IoT)” [1]. However, the state-of-the-art battery-powered IoT sensing nodes are incapable for dispersed and everlasting deployments. Especially in some applications, such as smart building and environmental monitoring, the labor cost for replacing or recharging batteries is too high to enable all the things with sensory ability [2], [3]. The battery-free solution is necessary and the only option for extensive and everlasting deployment of smart sensor networks. The energy harvesting (EH) technologies provide the feasibility of self-contained and self-powered IoT nodes by scavenging energy in different physical forms from the environment.

Compared with sensors powered by solar and radio frequency (RF), the deployment of vibration-powered sensors is not limited by illumination or RF signal intensity. It can be applied to any place where vibrations, or more generally speaking, 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. It was reported that walking could generate approximately 120-270 μW power [4]; writing, spinning in a swivel chair, or opening a drawer can provide 10-15 μW power [5]. Therefore, vibration energy harvesting (VEH) can serve as a complementary power solution in these scenarios, where illumination is poor (unsuitable for solar harvester), RF signal is weak (unsuitable for RF energy harvester), and the temperature difference is not significant (unsuitable for thermoelectric energy harvester).

Challenges: 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. For example, most vibration energy is sparsely distributed, which is not convenient for centralized utilization. The level of available vibration power is low, much lower than that of the grid power. Moreover, ambient vibrations are usually broadband. Some vibrations occur in intermittent mode, while some others might in transient mode. In general,
the design and optimization of vibration-powered IoT systems require a joint effort from many related disciplines, such as mechanical engineering, electrical engineering, computer engineering, and material science.

**Motivation:** Although the energy density of ambient vibration (about 200 μW/cm²) is larger than that of ambient RF waves (about 0.0002-1 μW/cm²) [6], compared with the formerly proposed RF-powered devices, such as RF-powered camera [7], [8], the vibration-powered IoT applications are less mature. Most of them are still at the developing stage of simple temperature or humidity sensing. Given the aforementioned challenges and aiming to power more wireless sensors in vibration environments, we develop a vibration-powered sensor node (ViPSN), which includes a full set of necessary modules of a vibration-powered IoT system. It serves as a reconfigurable developing platform for vibration-powered IoT applications. The whole set of ViPSN assembles six basic modules: a vibration emulator as the energy generation unit (EGU); a piezoelectric transducer as the energy transduction unit (ETU); a power-boosting interface circuit as the energy enhancement unit (EEU); a dc-dc regulator with energy-level indicating signals as the energy management unit (EMU); a Bluetooth low energy (BLE) module as the energy user unit (EUU); and a mobile app as the edge demonstration unit (EDU). All units or modules are connected with easy mechanical joggle joints and electrical plunger pin contacts. The system assembly and module breakdown are shown in Fig. 1.

**Contributions:** ViPSN is designed to promote the prosperity of the VEH research community. It offers standardized mechanical and electrical interfaces, as well as replaceable and extensible modules for handy customization of different vibration-powered IoT devices. The computer-aided design (CAD) model of mechanical frame, circuit schematics and printed circuit board (PCB) layout, and fundamental firmware codes are all open-source by Mechatronics and Energy Transformation Laboratory (METAL) at ShanghaiTech University.

The most significant contributions of ViPSN are in two folds:

- ViPSN is the first open-source development platform specified for vibration-powered IoT devices. It includes all necessary modules for rapid prototyping and customizing VEH systems. For almost two decades since the earliest literature, most VEH related studies emphasized in either transducer materials, mechanical dynamics, circuit design, or low-power electronics. An inclusive co-design, in particular, as an open-source project, is very helpful for promoting the concrete prosperity of VEH technology.

- In the EMU, by adding some complementary energy indicating signals, the stored energy is better monitored by the user module. Therefore, the software program can run more efficiently and robustly under various forms of vibration excitations, such as harmonic, intermittent, or transient cases.

**Outline:** The rest of this paper is organized as follows. Section II discusses the related work on battery-free IoT and vibration energy harvesting. Section III gives an overview of different modules of ViPSN. Section IV introduces some design considerations of its energy management towards more reliable utilization of the harvested energy. Section V describes the implementation details. Section VI provides experimental evaluations. Section VII concludes the paper.

## II. Related Work

### A. Battery-free IoT Systems

Energy harvesting technology enables maintenance-free and untethered power solutions for some low-power IoT systems, in particular, for those operating in hard-to-reach or dangerous places [1], [9]. Given the fluctuating feature of most ambient energy sources, there are more challenges by replacing conventional batteries with energy harvesting sources. In battery-free IoT systems, the operation somehow depends on energy income. In recent years, how to better coordinate different functions, such as energy harvesting, sensing, computing, and communication, in these systems has attracted many interests from the IoT research community. Research efforts have been devoted to reshape the hardware platforms, tools, programming languages, runtime, and intermittent networks towards such sustainable battery-free IoT systems. In particular, open-sourced hardware platforms enable developer communities to grow and thrive.

Advancements on solar energy harvesting made it possible to implement some IoT applications without using large battery storage. For example, Permamote [10], which integrates a photovoltaic (PV) harvester, a small backup battery, and the up-to-date low-power power components, can continuously operate for more than ten years as a sensor mote. In [11], a solar-powered, long-lasting autonomous image sensor is implemented for realizing rich-data acquisition. A trade-off was made by balancing all ingredients, such as non-volatile memory hierarchy, storage capacitor, harvester size, according to their dynamic energy burst scaling technique.

Besides using solar technology, some battery-free IoT devices were developed based on RF energy harvesting. WISP [12] is a battery-free sensing and transmitting platform based on RF sources. Since its release, WISP and its derivatives have become a preferred platform for the research of RF-powered IoT systems. WISP has extended the utilization of RF energy harvesting technology beyond passive Radio Frequency Identification (RFID) tags. One of its derivatives, WISPCam [7] is a passive wireless RFID tag with camera function. The RF wave acts simultaneously as a carrier of power and signal. Battery-free cellphone [13], which is powered by RF or photodiode harvesters, can sense speech, drive earphones, and switch between uplink and downlink communications, all in real-time. A battery-free video streaming camera [8] has also been implemented. Its power comes from a hybrid power harvester, which combines solar and RF technologies.

A more versatile platform, which is called Flicker, for prototyping battery-free embedded sensors was proposed in [14]. It supports solar, RF, and vibration energy harvesting sources, as well as a variety of peripherals, such as accelerometer, thermometer, Bluetooth and sub-1 GHz RF transceivers. The modular hardware can be reconfigured into

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1. https://github.com/METAL-ShanghaiTech/ViPSN
devices with multiple functions. The VEH module of Flicker has fully adopted the typical design of a commercialized IC LTC3588. Different from Flicker, ViPSN proposed in this paper enclosed six modules, which reflect a full consideration of the specific research and development demands of VEH-based IoT systems.

B. VEH Systems

A practical VEH system includes six necessary parts: vibration excitation, mechanical structure (harvester), transducer, interface circuit, energy storage (buffer), and dc load (IoT device) [15].

Excitation: The features of different mechanical vibration sources matter for the design of their corresponding VEH systems. The most studied excitations include constant flows [16], [17], harmonic [18], [19], periodic [20], [21], impulsive [22], [23], and stochastic [24], [25] vibrations.

Harvester: Given the mismatch between source and transducer, in terms of strain and stress range, resonant frequency, etc., mechanical structure designs are necessary for bridging these two parts. Tremendous efforts have been taken to match the strain ranges [26], [27] and operating frequencies [28]. In particular, regarding to the latter issue, people proposed various mechanical designs, such as resonance tuning [29], multi-mode harvester [30], frequency up-conversion [31], and nonlinear structure [32].

Transducer: An electromechanical transducer converts mechanical energy into electrical one. It is the key component for realizing the micro-energy generation. The transducers commonly used for VEH includes piezoelectric [33], electromagnetic [34], and electrostatic [35] ones. Among those transducers, the piezoelectric type has relatively simpler mechanical structures and easier power-conditioning circuits; therefore, it is more suitable for compact and self-contained applications.

Interface circuit: Interface circuit, which is immediately connected to a transducer, plays an essential role in harvested power improvement. It is a special ac-dc rectifier circuit, whose design should closely meet the specific features of different transducers and vibration sources. Many interface circuits were proposed for piezoelectric sources, such as standard energy harvesting (SEH) [36], synchronous electric charge extraction (SCE) [37], and synchronized switch harvesting on inductor (SSHI) [38]. Compared with SEH, the SCE and SSHI solutions can increase the harvesting capability by several folds. The sensing, synchronization, switch power, and switch control in SSHI can be realized in some self-powered solutions (SP-SSHI) [39]. In this study, an SP-SSHI interface circuit helps boost the harvesting capability of ViPSN towards a more robust operation.

Energy storage: The purpose of VEH technology is to replace large battery energy storage. However, it does not mean there is no energy storage device in a vibration-powered device. In a VEH system, given the probably unstable input power, a relatively small storage device is needed as the energy buffer for enhancing the reliability in operation. It was found in the previous studies that the supercapacitor is more suitable to be the energy buffer, given its higher power density and longer lifetime than chemical batteries [20].

DC load: The dc storage voltage needs to be regulated to a specific logic voltage level before driving digital circuits. Suitable regulators should be selected according to the source feature. For example, piezoelectric transducers give relatively high voltage output; therefore, a buck converter is usually used for voltage regulation. LTC3588 (Linear Technology Co.) is the most extensively used commercialized regulator specified for piezoelectric energy harvesting (PEH) [40]. In LTC3588, the internal under-voltage lockout (UVLO) threshold is fixed at 5 V (LTC3588-1) or 16 V (LTC3588-2), a better trade-off between larger energy storage and faster charging and responsive speed can only be made by carefully selecting a suitable storage capacitor. Additional design is necessary to guarantee the energy build-up process [41]. Such a design compromise has not received sufficient elaboration in the previous studies using LTC3588. This paper provides a complementary solution to relieve such a dilemma in practical designs.

IoT application: The vibration-powered IoT applications are not as mature as the solar and RF ones until now for two reasons. 1) The source dynamics of VEH are more complicated than solar and RF counterparts. Holistic design requires substantial idea exchange with dynamicists. 2) 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. Although there are difficulties for holistic design and optimization, there do have some successful prototypes, and even products demonstrated recently. Trinity [42], which is powered by airflow induced vibration, is a self-sustaining and self-contained indoor sensing system. It monitors the wind speed and temperature for heating, ventilation, and air conditioning (HVAC) system. A pair of self-powered smart shoes was proposed in [41]. It harvests energy from human walking or running by using piezoelectric transducers. It supports multi-functions, including step sensing, processing, and wireless communication with smartphones. Example products include the batteryless switch developed by EnOcean GmbH. [43] and the batteryless train bearing monitoring system developed by Perpetuum Ltd. [44]. These products either carry out easy functions or have a relatively large size. For VEH technology, it is necessary and challenging to make better synergy among mechanical, electrical, and cyber parts.

III. ViPSN Modules

The hardware architecture of ViPSN is shown in Fig. 2. It encapsulates five units: EGU, ETU, EEU, EMU, and EUU. Besides the hardware, an EDU with customized app receives standard BLE signals sent from EUU for demo purpose.

A. EGU

For EGU, a commercial portable resonance speaker serves as the vibrator. It generates vibrations according to the records from real-world environments. It is self-contained with a battery pack inside and standard auxiliary port (AUX) for audio input. Different from a normal loudspeaker, it does not have a diaphragm. It produces sounds by vibrating the
contacting hard medium. In other words, a resonance speaker can convert the audio signal into structural vibration. Compared with the expensive and heavy professional vibrator, this portable solution is a better option for the developer working on vibration-powered IoT applications.

B. ETU

For ETU, the piezoelectric transducer is made of a circular low-cost piezoelectric buzzer, whose rim is fixed at the moving part of the resonance speaker. The low-cost generator is good for popularization. If this cheap and under-performing structure works well, there is no doubt for other more sophisticated designs. A mass is bonded at the center of the round-shape transducer, as shown in Fig. 2(a). When the base (moving part of the vibrator) undergoes vibration, the piezoelectric structure deflects. Such base excitation can be modeled with the following dynamic equation:

\[-M\ddot{y}(t) = M\ddot{x}(t) + D\dot{x}(t) + Kx(t),\]

where \(\dot{y}\) is displacement of the vibrating base, \(x\) is relative beam deflection; \(M, D, K\) are mass, damping coefficient, and stiffness of the piezoelectric structure, respectively. The relation between input \(y\) and output \(x\) can be expressed as follows in the frequency domain

\[X(s) = \frac{s^2}{Y(s)} = \frac{s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2},\]

where \(\omega_n = \sqrt{K/M}\) is natural frequency, \(\zeta = D/2\sqrt{MK}\) is damping ratio. From (2), the base-excited ETU acts as a high-pass unit-gain filter, whose cutoff frequency is \(\omega_n\). Given a specific piezoelectric structure, the resonance and pass band can be tuned by adjusting the weight of the proof mass; therefore, the base-excited structure is good at reproducing the vibration excitation above the designed \(\omega_n\).

C. EEU

Under vibration excitation, the piezoelectric transducer produces an alternating or fluctuating voltage. We can use a simple full-wave bridge rectifier for ac-dc power conversion, in order to power digital electronics. The full-wave bridge, i.e., SEH is regarded as the benchmark interface circuit for PEH. In this design, an SP-SSHI interface circuit is adopted. SP-SSHI increases the harvested power by realizing running power factor correction [45]. Like most renewable sources, such as solar and wind ones, maximum output power, but not conversion efficiency, is the most important design criteria of the interface circuit (first stage power conditioning circuit). Compared with SEH, SP-SSHI can harvest a larger amount of energy under the same vibration excitation.

A piezoelectric structure can be modeled as an equivalent current source \(i_{eq}\) in parallel with its clamped capacitance \(C_p\) and dielectric leakage resistance \(R_p\), as shown in Fig. 3. The equivalent current source is proportional to the relative velocity, i.e.,

\[i_{eq}(t) = \alpha \dot{x}(t),\]
where $i_{eq}$ is the equivalent current source, and $\alpha$ is the force-voltage factor of the piezoelectric structure. Because displacement $x$ is alternating in vibration, $i_{eq}$ is also alternating. Thus, the voltage $v_p$ across the clamped capacitance $C_p$ is alternating. SEH uses a bridge rectifier and filter capacitor to convert the ac input into a smooth dc output. However, using SEH cannot ensure that the energy is always flowing from mechanical part to electrical part. In SEH, there is a phase difference between the zero-crossing points of $i_{eq}$ and piezoelectric voltage $v_p$, as shown by the dotted and dashed lines in Fig. 3(b). Therefore, energy returns from electrical part to mechanical part in some intervals [46].

The SP-SSHI circuit [39] overcomes this problem by adding a synchronized switch branch in parallel with the piezoelectric output, as shown in Fig. 3(a). An inductive synchronized switch branch can make a rapid voltage inversion for $v_p$ when $i_{eq}$ crosses zero, as shown by the solid line in Fig. 3(b), so the extracted power becomes always positive. In other words, it maintains unidirectional energy conversion from mechanical to electrical domains. The envelope detectors and comparators are used for detecting the extreme instants of $v_p$, which are equivalent to the zero-crossing instants of $i_{eq}$ and carrying out switching actions. The positive envelope detectors are composed of $R_1$, $D_1$, and $C_1$. The transistors $T_1$ acts as a comparator comparing the base voltage ($v_p$) and the emitter voltage ($v_p$ envelop). Once $v_p$ attains a maximum value and begin to drop, $T_1$ conducts. The current from $T_1$ collector turns on the corresponding transistor switch $T_3$. An inductive switching path is formed by $D_3$, $T_3$, and inductor $L_1$. It realizes a rapid positive to negative voltage inversion for $v_p$. The complementary part of the circuit is used for negative-to-positive voltage inversion at minimum $v_p$. More detailed principle of SP-SSHI can be referred to [39, 45].

The charging history of the storage capacitor ($V_{store}$) with different interface circuits, i.e., SEH and SP-SSHI, is shown in Fig. 4. The charging tests are carried out with a 120 Hz harmonic excitations at different vibration levels (acceleration magnitudes ranges from 0.33, 0.43, to 0.80 g). The minimum start-up voltage of the buck converter for generating a constant output voltage is $V_{store} = 5$ V. As we can observe from Fig. 4, under small excitation, i.e., 0.33 g acceleration, neither SP-SSHI nor SEH can reach this 5 V threshold. When acceleration magnitude rises to a critical value 0.43 g, SP-SSHI can make the task, but SEH cannot. Both SEH and SP-SSHI can properly work under 0.80 g excitation. Yet, when fully charged, under this excitation level, SP-SSHI can offer $(13.5/8.2)^2 = 2.71$ folds of energy, compared with SEH.

D. EMU

In a VEH system, EMU plays an essential role to guarantee the robust and reliable operation under complicated vibration conditions. It is responsible not only for providing temporary capacitive energy storage for the extra harvested energy from ETU, but also for supplying power at a constant voltage to EUU. On the other hand, many vibration sources are intermittent, variable, and unpredictable, so vibration-powered devices should operate in various vibration environments, such as intermittent mode or transient mode. EMU has to maximize the harvested energy income from the supply side, minimize the energy dissipation in energy conversion, and properly deliver power on the user’s demand. The software program should be carried out with an awareness of the stored energy level. However, most off-the-shelf commercial regulators IC only emphasized stable logic voltage output. Necessary interactions between energy storage and EUU were not sufficiently supported. For example, LTC3588, as mentioned in Section II-B, integrates a low-loss full-wave bridge rectifier and a high-efficiency buck converter for PEH power conditioning. Its power good output pin (PGOOD) is actually used for indicating the availability of stable output voltage, rather than the stored energy level [40].

In this paper, an enhanced EMU is developed by making complementary design to LTC3588. It produces necessary energy-level indicating signals to the energy user for better operation under fluctuating or intermittent vibrations. As shown in Fig. 2(c), the EMU has three parts: a dc-dc buck converter, an energy storage capacitor, and a comparator with adjustable hysteresis. An external comparator is responsible for detecting the energy level of the storage capacitor. Two additional energy-level indicating signals $P_{good}$ and $P_{close}$ are added beyond the two internal fixed-level UVLO signals ($P_{start}$ and $P_{close}$) in LTC3588.

During the operation, the EMU provides two internal energy-level indicating signals to itself and three external signals to the EUU, such that ViPSN can properly handle different tasks. $P_{start}$ sets when $V_{store} > 5$ V and $P_{close}$ sets when $V_{store} < 3.4$ V. $P_{start}$ starts the dc-dc power conversion of LTC3588. $P_{close}$ turns off the converter. There might be several rounds of lockouts and restarts before the output voltage reaches a stable level, because of the depletion and refill of the storage capacitor. Besides the fixed UVLO thresholds, the PGOOD pin of LTC3588 offers further information on the output voltage stability. The PGOOD pin is logic high when the output voltage of LTC3588 is above 92% of the desired regulation voltage (3.3 V in this study). If $V_{cc}$ falls below this threshold, it turns to logic low. It should be noted that PGOOD is not a storage-level indicating signal. $P_{good}$ added in this study provides a real storage-level indicating signal. It comes with the rising edge of the comparator’s output.
denotes that the storage capacitor of EMU has gained sufficient energy to ensure the execution of the most power-consuming atomic operation. \( P_{\text{sleep}} \) comes with the falling edge of the comparator’s output. It warns that the energy storage of EMU is in shortage; therefore, the EUU must take an emergent process to save the critical data and then go to the ultra-low-power deep-sleep mode. In addition, via adjusting the resistor network of the comparator, we can change the voltage thresholds for generating \( P_{\text{good}} \) and \( P_{\text{sleep}} \) so as to ensure proper operations under different excitation conditions.

E. EUU

A BLE node as the EUU is used to carry out temperature sensing and transmitting functions. Fig. 5(a) and (b) show the storage voltage profile and the current consumption in a whole operation cycle under harmonic excitation. First, the capacitor needs to be charged above \( V_{\text{Pstart}} \) the UVLO rising threshold, such that the dc-dc regulator starts. Once \( V_{CC} \) attains the minimum workable digital level, it performs the most necessary initialization, then immediately goes to sleep and wait for stable supply voltage, which is indicated by \( P_{\text{GOOD}} \). Under a stable supply voltage, further initialization can be carried out. The energy build-up phase starts as well. During the energy build-up phase, EUU stays in deep-sleep mode and waits for the \( P_{\text{good}} \) interrupt indicating there is sufficient stored energy, such that to avoid wasting the harvested energy. This phase ends until the storage voltage reaches the \( V_{\text{Pgood}} \) threshold. After the EMU setting \( P_{\text{good}} \), EUU starts to execute some functions. In the periodical sensing and transmitting phase, ViPSN periodically senses the temperature and transmits the signal to the remote receiver. To keep ViPSN in the power-on state for a longer time, EMU also sends out a \( P_{\text{sleep}} \) interrupt signal at the falling edge of the comparator output. With this low-energy indicating signal, EUU could stop executing energy-consuming functions and enter the deep-sleep phase. Energy build-up process restarts. ViPSN remains in hibernation until the next round of intensive vibration.

IV. EMU DESIGN CONSIDERATIONS

As an IoT platform designed for developers, who want to build vibration energy harvesting battery-free devices, ViPSN provides a solution to better coordinate the energy income and IoT demands. It should be adaptive to a wide range of vibration excitations, including the intermittent and fluctuating ones. It should also be reconfigurable to support a wide range of peripherals regarding their operation features and power requirements. EMU plays an essential role in fulfilling these tasks.

A. Energy build-up phase

Fig. 6 shows the voltage traces of ViPSN in operation with or without energy indicating signals. Fig. 7 further illustrates the energy quotas in the conventional fixed storage thresholds scheme offered by LTC3588 and the new ViPSN EMU solution with two more tunable thresholds. Under the same harmonic excitation, ViPSN with energy indicating signals can perform sensing and transmitting operations successfully even using a small capacitor as energy buffer. When there is no energy indicating signal, ViPSN cannot provide a stable voltage \( V_{CC} \). Because the available energy, which is determined by the fixed \( V_{\text{Pstart}} \) and \( V_{\text{Pclose}} \) threshold, i.e., \( \frac{1}{2} C_r (V_{\text{Pstart}}^2 - V_{\text{Pclose}}^2) \), might be sufficient to energize neither initialization nor normal operation. Under such condition, the system cannot successfully start up, given the continuous power supply outage, as shown in Fig. 6(a) and the corresponding red segment.
peak power 5.85
Duration
Energy
4.0
4.1
34.3
0.7
42.2
8.0
1.2
Average power
8.0
86.1

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Fig. 7: Storage energy versus threshold voltages under different storage capacitance. (a) and (c) Conventional scheme without energy indicating signal. (b) and (d) ViPSN EMU with two energy indicating signals. V_{P_{start}} and V_{P_{close}} are fixed thresholds, while V_{P_{good}} and V_{P_{sleep}} are tunable according to the most energy-consuming atomic operation.

TABLE I: ViPSN power and energy statistics.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Peak power (mW)</th>
<th>Duration (ms)</th>
<th>Energy (µJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialization</td>
<td>86.1</td>
<td>4.1</td>
<td>26.8</td>
</tr>
<tr>
<td>Sensing</td>
<td>8.0</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Transmitting</td>
<td>34.3</td>
<td>4.0</td>
<td>32.2</td>
</tr>
<tr>
<td>Operation</td>
<td>Average power (µW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeping</td>
<td>5.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static power</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6: Operation phases with or without additional energy indicating signals under the same harmonic excitation (magnitude: 0.97 g, frequency: 150 Hz). (a) Unsuccessful startup using small storage capacitor (C_f = 10 µF) without additional energy indicating signal. (b) Successful but slow startup using large storage capacitor (100 µF) without additional energy indicating signal. (c) Successful startup using small storage capacitor (10 µF) with additional energy indicating signals.

The absolute energy quota provided by the storage in the Fig. 6(a) case is 67 µJ, which is more than the required energy for initialization as listed in Table I. However, considering that conversion efficiency is not perfectly 100%, 67 µJ stored energy is still insufficient to initialize ViPSN.

viPSN can better operate under different vibration conditions by tuning the V_{P_{good}} level. Especially, in transient mode vibration, the energy that can be harvested is limited, we can lower the threshold (V_{P_{good}}) for generating P_{good}, so that EEU can be activated more rapidly after initialization and then complete the easy transient sensing and transmission tasks. In continuous vibration, we can increase the threshold for generating P_{good} accordingly, so as to provide sufficient energy to EEU for performing more comprehensive tasks. It is also possible to shorten the active period by increasing the threshold (V_{P_{sleep}}) for generating P_{sleep}. Given that ViPSN is driven by an intermittent vibration, starting from a higher level of residual energy can shorten the next energy build-up interval.

Via the energy-warning interrupt signal P_{sleep} offered by EMU, EEU can keep track of the energy storage condition passively and economically. The passive solution consumes less power than the energy-expensive active polling, which samples the storage voltage all the time. More importantly, in this EMU solution, the V_{P_{good}} and V_{P_{sleep}} thresholds can be tuned by adjusting the resistor ladder according to the energy demands of all atomic operations of EEU, as shown in Fig. 7(c) and (d). ViPSN is ready to be extended to embrace more types of peripherals. EEU does not need to be reprogrammed for energy monitoring. It enables developers to create new applications more easily.

B. Energy consumption and storage capacitor selection

The amount of energy stored in EMU should be estimated according to the harvested power, on-demand dynamic energy consumption, and static power. The equation governing the time-dependent energy level in the stored capacitor is formulated as follows:

\[
\eta \left[ \int_{t_0}^{t} P_h(\tau) d\tau - E_{store}(t) \right] = \int_{t_0}^{t} P_{static}(\tau) d\tau + \sum_{i} E_{task,i} \tag{4}
\]

where \( P_h \) is the harvested power, which is obtained after the EEU. \( \eta \) is the average dc-dc energy conversion efficiency. The
EUU carries out various tasks, including initialization, sensing, transmitting, and sleeping. The energy consumption $E_{\text{task},i}$ of these tasks are listed in Table I. $P_{\text{static}}$ represents the static power consumption of the system. It includes the operating power of comparator $P_{\text{comp}}$, buck converter $P_{\text{dc-dc}}$, and leakage power $P_{\text{leak}}$, which is caused by the parallel leakage resistor of the storage capacitor. Considering these non-negligible energy consumption, $P_{\text{static}}$ is summarized as follows:

$$P_{\text{static}}(t) = P_{\text{comp}}(t) + P_{\text{dc-dc}}(t) + P_{\text{leak}}(t).$$

Owing to the UVLO capability, the buck converter will not turn on until the storage voltage ($V_{\text{store}}$) reaches the UVLO threshold ($V_{\text{UVLO}}$), as shown in Fig. 6. During the cold-start phase, there is only $P_{\text{leak}}$ leakage power consumption. However, the buck converter has a much higher power consumption during operation. That explains the sudden storage voltage drops in the initialization phase, as shown in Fig. 4 and 5(a). In addition, once the converter is switched on, the system starts to perform initialization, in which the comparator and EUU are enabled at the same time. As shown in Fig. 5(b), the load current reaches a peak value during the initialization phase. Therefore, in this study, initialization is the most energy-consuming task. More generally speaking, the storage capacitor needs to satisfy (6) and (7), so that the system has enough energy to exit the cold-start phase, and complete the most energy-consuming task.

$$C_{\text{store}} \geq \max \{C_i\},$$

$$C_i = \frac{2}{\eta} \left[ \int_{T_i} P_{\text{static}}(t) \, dt + E_{\text{task},i} \right].$$

In (6), $C_{\text{store}}$ indicates the value of the storage capacitance; $C_i$ and $V_{\text{task},i}$ represents the minimum capacitance and voltage threshold for successfully carrying out the $i^{\text{th}}$ task. In this design, the minimum kick-off voltage $V_{\text{task},i}$ for initialization is $V_{\text{UVLO}}$ (5 V). Other $V_{\text{task},i}$ must be larger than $V_{\text{Pclose}}$ (3.4 V) to avoid sudden power outage.

V. IMPLEMENTATION

A. Hardware

A prototyped ViPSN is implemented, as shown in Fig. 1. The specifications are listed in Table II. An LTC3588-1 IC is used for regulation purpose. Its dc-dc power conversion efficiency is around 80% to 90% under different input voltage, output voltage, and loading current [40]. MIC841 [47], a micro-power, precision-voltage comparator with adjustable hysteresis is used to provide energy indicating signals. A programmable BLE SoC (system on chip) nRF52832 by Nordic Inc. [48] serves as the EUU. The EUU has three parts: transceiver, sensor, and CPU. The sensor part uses the on-chip temperature sensor in nRF52832. Two remote edge devices are designed for receiving the signals sent out by ViPSN. One is a cell phone, which runs a customized mobile app, as shown in Fig. 1(c). Another is a host PC, which installs a USB BLE receiver module and data processing program.

B. Overhead and minimum storage capacitor

The statistics of power and energy of different tasks are shown in Table I. Before performing regular sensing and transmission tasks, for both EUU and EUU, the initialization phase is necessary. So the harvested energy must first satisfy the initialization consumption. The listed initialization energy consumption (56.8 $\mu$J) is the sum of the initial configuration power of the buck converter, comparator, and EUU. The static average power consumption of EMU (8.0 $\mu$W) includes that of the comparator, buck converter, and leakage power. The minimum storage capacitance can be derived as 8.46 $\mu$F according to (7). Since initialization is the most energy-consuming task in this study, this is the minimum capacitance for ensuring successful initialization.

C. Dependability communication

In this study, we use Enhanced ShockBurst (ESB) [49] for dependability wireless transmission. ESB is a basic protocol that supports two-way data packet communication, including packet buffering, packet acknowledgment, and automatic retransmission of lost packets. It supports a star network topology with one receiver and up to 8 transmitters. For ViPSN, energy and its relationship to wireless communication is a critical subject. Fig. 8 shows a typical wireless communication process with several important parameter configurations that can be optimized to accommodate the vibration-powered system. For enhancing the transmission reliability, the transmitter has opportunities to retransmit the packet until the ACK is finally received. In this case, considering the trade-off between the reliability and power consumption power, we set the delay as 600 $\mu$s and the retransmission number as 3.
Fig. 9: The workflow of ViPSN under intermittent mode excitation. (a) $V_{\text{store}}$ and $V_{\text{cc}}$ under the bridge vibration excitation. (b) Acceleration at location #1. (c) Enlarged view during initialization. (d) Enlarged view during periodical sensing and transmitting.

Fig. 10: Acceleration records at three spots of the Clifton Suspension Bridge in UK.

Fig. 11: The performance of ViPSN under simulated bridge vibrations. (a) QoS. (b) Power lifetime.

VI. EVALUATION AND CASE STUDY

A. Setting

Via configuring the thresholds of $V_{\text{PGood}}$ and $V_{\text{PSleep}}$, ViPSN can perform new use cases and applications under different excitation conditions, including intermittent and transient vibrations. We evaluate the performance of ViPSN based on the power lifetime and quality of service (QoS). The power lifetime means the time when EUU remains power on. The QoS is the number of successful packets transmitted by ViPSN.

B. Harmonic vibrations

Fig. 5 shows the operation under harmonic vibration, whose duration is 48 s, frequency is 150 Hz, and peak acceleration is 1.67 g. In the experiment, we use a 47 µF capacitor as the storage component in EMU. Fig. 5(e) shows the enlarged view of the current waveform in one round of temperature sensing and transmission. The system wakes up from low-power mode, and immediately carries out temperature sampling, pre-processing, and crystal upgrading, finally processes and transmits the data. Fig. 5(f) shows the current waveform in the initialization phase.

C. Intermittent vibrations

In this case, we use the resonant speaker to simulate the real-world vibration of a suspended bridge. The vibration data set is provided by the Energy Harvesting Network Data Repository\(^3\). It is an online repository that provides a common resource for sharing data on energy availability. The data used in the 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.

Fig. 10 shows the vibration records at three positions. Location #1 is at the end of the suspended bridge segment, which is close to the pillars. Location #2 and location #3 are on the protective metal railing, which separates the sidewalk. In our study, we use a GY-61 DXL335 3-axis accelerometer module [50] for providing feedback, such that to make sure the reproduction of the bridge vibration is credible.

We configure ViPSN to periodically sense the local temperature and transmit the result to the host device. In order to fulfill such periodic tasks, we select a 47 µF storage capacitor. We set the voltage thresholds $V_{\text{PGood}}$ and $V_{\text{PSleep}}$ as 6.6 V and 5.5 V, which guarantee that the system can perform at least 5 rounds of temperature sensing and transmissions.

As shown in Fig. 9(a) and (b), we record the traces of $V_{\text{store}}$, $V_{\text{cc}}$, and acceleration at location #1. The peak acceleration of this vibration excitation is around 2 g, and the duration is

\(^3\)http://eh-network.org/data/
Fig. 12: The workflow of ViPSN under transient mode excitation. (a) $V_{\text{store}}$, $V_{cc}$ of ViPSN with SP-SSHI. (b) Enlarged view of the transient transmitting and excitation. (c) Burst vibration acceleration. (d) Enlarged view of the excitation.

Fig. 13: The performance of ViPSN under pulse excitation. (a) QoS. (b) Power lifetime.

D. Transient excitation

In this case, we use a transient signal to excite the speaker. ViPSN is reconfigured to catch this burst-mode vibration energy. As shown in Fig. 12(c), the transient excitation only lasts for 780 ms. Its peak acceleration is around 2 g. In response to such a transient mode vibration excitation, we choose a 10 $\mu$F storage capacitor, whose capacitance is above the lower limit of successful operation. In order to shorten the duration of the cold-start and energy build-up phases, we tune the voltage threshold $V_{\text{Pgood}}$ to 5.0 V, which is the same as $V_{\text{Pstart}}$.

For this case, we set ViPSN to do one transmission as soon as $P_{\text{good}}$ is triggered, which is different from the periodic tasks. As shown in Fig. 12, through the power conditioning process of the SP-SSHI interface circuit and the optimized EMU and EUU, ViPSN can carry out six rounds of transmitting functions and later maintain the power-on state for up to 10 seconds. However, as reliable transmission requires an accurate and stable high-frequency clock, we can observe some transmission failures during the unstable $V_{cc}$ period (1.38-1.53 seconds) in the cold-start phase.

We also compare the performance of ViPSN when using SP-SSHI or SEH. Fig. 13 shows that, under the transient excitation, ViPSN can achieve better QoS and longer power lifetime when using SP-SSHI. The QoS with SP-SSHI is about 1.5 times of that with SEH.

VII. CONCLUSION

This paper introduced ViPSN, a new open-source IoT platform built for vibration energy harvesting, battery-free sensing, and computing. Based on the specific design considering various vibration conditions, ViPSN can harvest considerable energy under harmonic, intermittent, or transient mechanical vibrations for supporting different types of IoT functions. By using ViPSN, developers with different academic backgrounds can quickly prototype their vibration- or motion-powered devices towards new applications in different scenarios.

We implemented ViPSN in the modular forms in order to support rapid reconfiguration and future extensibility. We evaluated the
usability and performances of ViPSN in three study cases. The results show that the prototyped ViPSN device can robustly operate under different forms of vibration excitations. We look forward that ViPSN can make a valuable contribution to the prosperity of both research communities of vibration energy harvesting and battery-free IoT systems.

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