ECOVIBE: On-Demand Sensing for Railway Bridge Structural Health Monitoring

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***Abstract*—Energy efficient sensing is one of the main objectives in the design of networked embedded monitoring systems. However, existing approaches such as duty cycling and ambient energy harvesting face challenges in railway bridge health monitoring applications due to the unpredictability of train passages and insufficient ambient energy around bridges. This paper presents eco-friendly vibration (ECOVIBE), an on-demand sensing system that automatically turns on itself when a train passes on the bridge and adaptively powers itself off after finishing all tasks. After that, it goes into an inactive state with *near-zero* power dissipation. ECOVIBE achieves these by: first, a novel, fully passive event detection circuit to continuously detect passing trains without consuming any energy. Second, combining train-induced vibration energy harvesting with a transistor-based load switch, a tiny amount of energy is sufficient to keep ECOVIBE active for a long time. Third, a passive adaptive off control circuit is introduced to quickly switch off ECOVIBE. Also this circuit does not consume any energy during inactivity periods. We present the prototype implementation of the proposed system using commercially available components and evaluate its performance in real-world scenarios. Our results show that ECOVIBE is effective in railway bridge health monitoring applications.**

***Index Terms*—On-demand sensing, smart transportation, structural health monitoring (SHM), vibration energy harvesting.**

I. INTRODUCTION

STRUCTURAL health monitoring (SHM) for railway bridges is becoming an increasingly relevant requirement in transportation infrastructure management. According to statistics from 17 European railway administrations [1], there are more than 73 000 railway bridges older than 110 years, which comprises 35% of the railway bridges in Europe. More than 31% of all bridges are between 60 and 110 years old. The situation is similar in Sweden, where 53% of the railway bridges are over 50 years old [2]. Currently, the Swedish Transport Administration spends around 0.1 billion Euro annually for bridge operation and maintenance.

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The Internet of Everything (IoE) [3]–[5] provides an appealing solution for railway bridge surveillance, condition assessment, and management. It promises low costs, intelligent services, and efficiency. Many smart motes with various kinds of sensors are placed on the railway bridge. They record information when trains pass by and transmit the gathered data to edge devices through low power wireless access technologies. Edge devices can perform primary data analysis and filtering. After that, the data is submitted to cloud service platforms for storage and high level processing. Finally, the transport administration could make strategic plans for inspection and maintenance based on diagnostic reports.

Energy efficient sensing is a crucial issue in IoE-based SHM, since it enables long-term, efficient monitoring with minimal maintenance of the sensor devices. However, existing energy efficient solutions such as *duty cycling* and *ambient energy harvesting* face challenges in railway bridge monitoring applications as follows.

A. Unpredictable Passing Trains

Strain cycles and vibrations induced by trains are the most valuable data for structural experts [6]–[8], to evaluate the remaining fatigue life of railway bridges. The exact arrival time of trains at the bridge, however, is hard to predict. Based on time tables we can only infer that the train should arrive during a certain period, rather than at an exact time. Therefore, efficient scheduling of the sensing periods is critical for both network lifetime and quality of service. Frequent and long sensing periods lead to high energy consumption. This is especially true for railway bridge health monitoring applications, since the sensors used can be power-hungry. For example, the power consumption of a strain gauge is up to 60 mW [7]. Moreover, too frequent wake-ups generate unnecessary data which increases the burden of processing and communication, resulting in further energy waste. Although, increasing the wake up interval could partly mitigate the above problem, the risk of missing train passing events increases.

B. Insufficient Ambient Energy

Sunlight and vibration induced by trains are promising candidates for ambient energy sources. Sunlight has a high energy density but is not suitable for railway bridge scenarios where sensor nodes are placed under the bridge away from sunlight. Vibration energy, on the other hand, has a much

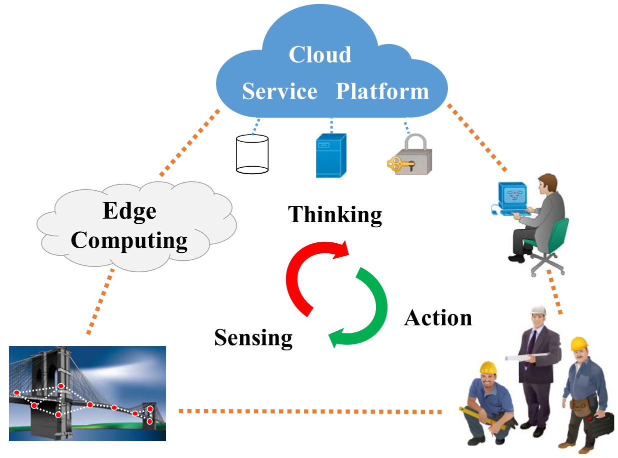


Fig. 1. IoE for SHM.

lower power density, from hundreds of μW to several mW [9]. In addition the passing trains are infrequent and transient, severely limiting the amount of vibration energy that can be harvested. For example, the time interval between commuter trains across the Lidingö bridge in Stockholm varies from 3 min to 20 min during daytime, with longer intervals during nighttime. The train passes a certain location in less than 10 s. These conditions make energy management essential for optimizing the monitoring system performance [10]–[12].

In this paper, we address the above challenges by designing eco-friendly vibration (ECOVIBE), an on-demand sensing system for railway bridge health monitoring. Rather than duty cycling the sensors based on a predefined schedule, ECOVIBE is able to adaptively wake up when trains are passing on the bridge. Therefore, ECOVIBE efficiently avoids redundant sampling and the risk of missing train events. Second, sensor nodes would be idle most of the time as train events occur on rare occasions. Hence, minimizing idle energy consumption is important toward the dream of self-sustaining systems in environments without sufficient ambient energy. Relying on fully passive circuit design of event detection and adaptive off control, ECOVIBE achieves near-zero energy dissipation during idle periods. The main contributions of this paper are summarized as follows.

1) To the best of our knowledge, ECOVIBE is the first railway bridge monitoring system that provides on-demand sensing with near-zero idle energy dissipation.
2) We establish an energy consumption model and compare ECOVIBE with state-of-the-art monitoring systems. The results show that ECOVIBE is more energy-efficient in rare events applications.
3) We implement a prototype of ECOVIBE using commercial off-the-shelf components, and evaluate its performance in field tests.
4) We believe that the working principle behind ECOVIBE can be also applied to other vibration-based event applications.

From the perspective of civil engineering, parameters such as strain, force, displacement, acceleration, and temperature are important for bridge condition assessment [8]. Each node usually features one or more types of sensors. Strain gauges are used to measure stresses and applied loads. Acoustic emission sensors detect bridge fatigue and crack. The frequency of train-induced vibrations is measured by accelerometers, and temperature sensors record ambient temperature conditions. In our ECOVIBE system, when the nodes wake up they turn on their sensors to collect bridge health information. The most time-sensitive data could be directly sent to the moving train and its driver for better train control. So both passenger safety and bridge health can be improved. The less time-sensitive data, as shown in Fig. 1, is sent from the edge [13] to the cloud for condition assessment and maintenance planning.

On the other hand, vibration occurs in moving human bodies, working machines, liquid flow, air flow, and passing vehicles [14], [15]. Benefitting from ECOVIBE's characteristic, namely on-demand sensing and energy harvesting, some potential applications that we imagine ECOVIBE could apply to are on-demand implantable/wearable sensing devices, autonomous industrial monitoring, smart water metering, and intelligent transportation systems.

The rest of this paper is organized as follows. Section II reviews related work. In Section III, we discuss ECOVIBE's system design in detail. The prototype implementation, energy consumption modeling and field tests are presented in Sections IV–VI. Finally, we conclude this paper in Section VII.

II. RELATED WORK

In recent years, many energy efficient sensing systems have been proposed for bridge health monitoring applications. They mostly adopt a cluster-based architecture, in which the cluster nodes are responsible to continuously monitor events of interest and broadcast *sensing commands* to noncluster nodes. The noncluster nodes wait for *sensing commands* from cluster nodes and start sensing their task upon receiving it.

BriMon [16] is a pure radio-based duty-cycled system, in which both cluster and noncluster devices duty cycle their radio. Devices mounted on the train constantly send beacons to announce train arrivals. The cluster nodes are placed before the bridge, and wake up periodically to check if a beacon is present. Upon detecting the beacon, the cluster nodes immediately send commands to other nodes for triggering condition sampling. Noncluster nodes also wake up periodically to check for sensing commands from the cluster nodes, and start bridge condition sampling if command is received.

Popovic *et al.* [17] proposed to use sensor-based cluster nodes that continuously monitor train-induced vibrations using low-power accelerometers, and radio-based duty-cycled noncluster nodes. In this way, the system does not require any devices on the trains. However, frequent idle listening of noncluster nodes still wastes much energy.

To mitigate the idle listening problem, noncluster nodes in SenetSHM [18] are equipped with wake-up radios [19]–[21] to detect the radio frequency energy of the beacons from clusters. The cluster nodes also use accelerometers to continuously measure vibrations, and transmit beacons when an event

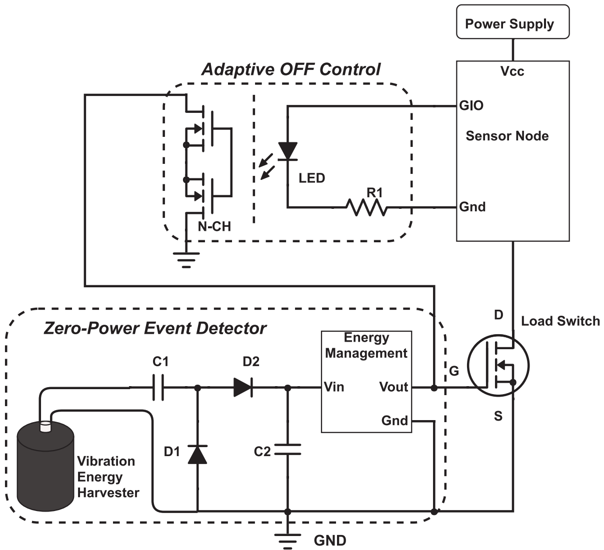


Fig. 2. Architecture and schematic of the EcoVibe system, it consists of (a) zero-power event detector, (b) load switch, (c) sensor node, (d) adaptive OFF control circuit, and (e) power supply.

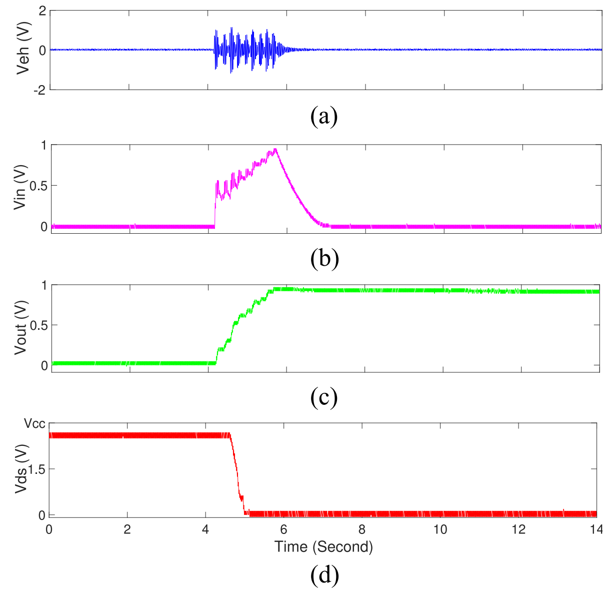


Fig. 3. Working principle of the energy harvesting-based event detection circuit. The traces from top to bottom are: (a) voltage converting from vibrations, (b) rectified voltage as input to the energy management, (c) output voltage of the energy management used as a wake up signal to turn on the switch, (d) after connecting the power supply rail, the analog ground of the sensor node goes from high level to low level.

is detected. Since only comparators and amplifiers dissipate power, the energy consumption of the noncluster nodes during idle period is significantly reduced.

EcoVibe improves these works in that: 1) rather than using a radio or low-power sensors for train detection, EcoVibe is able to detect passing trains passively; 2) to minimize idle energy dissipation, rather than being in low-power sleep or deep sleep mode, EcoVibe nodes are completely off when no train is passing and can be triggered to wake up by weak train-induced vibrations; and 3) EcoVibe can be deployed as a cluster-based network architecture, where one or more EcoVibe nodes are used as sentries. EcoVibe can also form a distributed network, where all nodes independently decide when to sense.

We previously presented EcoSense [22], a node architecture for on-demand sensing. In this paper, we make it ready for railway bridge health monitoring applications. Specifically, we investigate characteristics of train-induced bridge vibrations for the design of a high performance event detection circuit. We also design a novel control logic circuit that quickly powers off sensor nodes after they have finished their tasks. This circuit does not consume any energy.

III. EcoVibe Design

We design a monitoring system for railway bridge health monitoring applications. Our objective has the following two perspectives: 1) on-demand sensing and 2) minimizing idle power dissipation. In this section, we first describe the architecture of EcoVibe, and then detail the key modules.

A. System Architecture

As illustrated in Fig. 2, EcoVibe's system architecture consists of five modules: 1) a zero-power event detector; 2) a load switch; 3) a sensor node; 4) an adaptive off control circuit; and 5) a power supply. The event detector's responsibility is to determine whether a train is coming or not. When detecting a train, it generates a trigger signal to the load switch to turn on the power supply of the sensing system. After that, the activated sensor node starts to measure the bridge condition. Finally, when the node finishes its tasks, it sends a signal to the load switch through the adaptive off control circuit in order to power off itself. The power supply could be provided by batteries, environmental energy harvesting, or heterogeneous energy sources.

B. Zero-Power Event Detector

The dynamic and unpredictable nature of trains mandates that the event detector has to continuously monitor the environment. Therefore, energy efficiency is a big concern in event detection circuit design. Normally, ultralow power analog circuits are adopted to perform persistent sampling and generate an interrupt to wake up sensor nodes from sleep mode. These circuits consist of an ultralow power sensor, amplifier, comparator, and other active components. Although these event detection circuits are ultralow power, the continuous event detection still wastes much energy, which is a problem in environments with insufficient ambient energy.

To address this issue, we design a zero-power event detection circuit. It solely relies on passive electronic components to detect passing trains and generate wake-up interrupts. Fig. 2 presents the detailed design of the *Zero-Power Event Detector* subsystem. It includes a vibration energy harvester, a rectifier, and an energy management unit. The vibration energy harvester is used as a passive sensor to continuously monitor and detect vibrations from trains. Since the harvester does not require power, significant energy is saved during the period of event detection. For interrupt generation, we merely rely on the harvested energy stored in the energy management unit to wake up the sensor node, rather than additionally generating an interrupt through a comparator. This design leads to

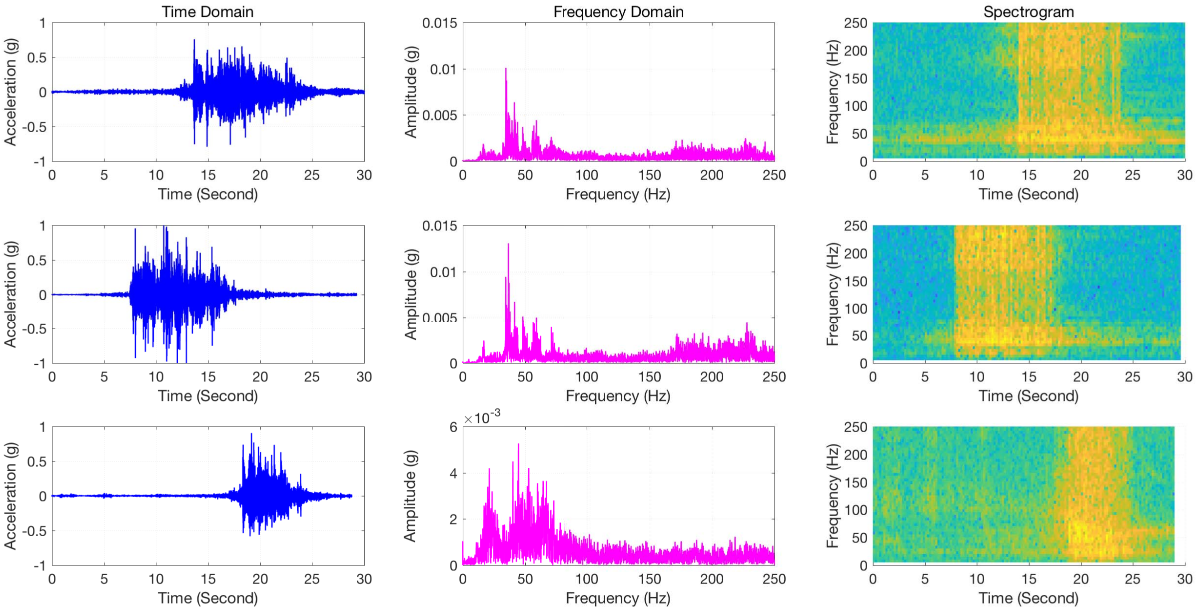


Fig. 4. Vibrations of the Lidingö bridge induced by a commuter train in time domain, frequency domain, and spectrogram. The data in the top two rows are measured on the guard rail between pedestrian and railway track, and the bottom plots are vibrations on the wooden beam.

zero power dissipation during inactivity periods. Moreover, tiny energy extracting from weak vibrations is enough to activate the sensor node working a long time as we show in Section III-D (50 μJ of energy can trigger sensor nodes to work for more than 5 min).

Fig. 3 depicts the working principle of the zero-power event detection circuit. When a train approaches, the induced vibrations on the railway bridge are converted into electrical energy. The blue trace at the top shows the voltage generated by the vibration energy harvester. At the same time, the rectifier converts the ac voltage to dc voltage for energy storage. The second purple signal is a voltage trace after rectification. Specifically, a 1-stage modified Dickson charge pump is chosen as rectifier since it not only performs rectification but also doubles the output voltage. This property is very useful to rapidly wake up sensor nodes because the load switch cannot be closed if the input is below a threshold voltage. The third trace is the voltage across a storage capacitor and the open/close status is shown in the bottom trace. As soon as the voltage across the storage capacitor reaches the threshold of the N-channel metal oxide semiconductor field effect transistor (MOSFET) switch, the sensor node is activated.

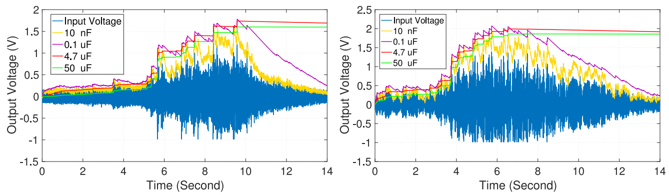
C. Sensitivity

In order to improve the event detector's sensitivity, we need to understand the characteristics of train-induced vibrations on the railway bridge, such as acceleration and frequency response, so that we can select a suitable vibration energy harvester. For this purpose, we study the characteristics of vibrations on the target railway bridge, the old Lidingö bridge in Stockholm. We use a Texas Instruments SensorTag node to measure the vibrations induced by the train. The sample rate of the tri-axis accelerometer is set to 504 Hz. Fig. 4 demonstrates the z-axis acceleration waveform in the time domain, the frequency domain, and its spectrogram. The first two traces are collected from vibrations on the guard rail between the pedestrian/bicycle path and railway track. The third one is measured on a wooden beam.

In terms of time domain, the peak accelerations are 0.79g, 1.09g, and 0.91g, respectively. The spectrum analysis indicates that the dominant frequencies are in the range of 35–45 Hz. Specifically, the peak amplitude in the first measurement occurs at 35 Hz with 0.01g acceleration, and 0.013g at 37 Hz in the second measurement. Although the peak vibration amplitude on the wooden beam (0.005g at 45 Hz) is much smaller than that on the guard rail from the frequency domain perspective, it has a wide bandwidth. Lastly, from the point view of the spectrogram, the dominant frequencies remain stable during the train passage.

Based on the analysis above, we derive the requirements for the vibration energy harvester: 1) extract kinetic energy also when the peak acceleration is small; 2) low resonance frequency (less than 50 Hz); and 3) reasonable operation bandwidth (such as 10 Hz). Piezoelectric and electromagnetic transducers are two popular commercially available vibration energy harvesters. Piezoelectric transducers have good performance when vibrations are strong and the frequency is high, which makes them suitable for harvesting energy from vibrations from manufacturing machines, vehicles [23], and air conditioning system applications [24]. Piezoelectric transducers, on the other hand, have a high output impedance. By contrast, electromagnetic transducers have a low output impedance and better energy output at low frequencies. In addition, the range of the operation frequencies is broader. Therefore, we select an electromagnetic transducer for ECOVIBE.

The sensitivity is also affected by the capacitor value and the electronic components' efficiency in the rectifier. Hence, it is important to determine the optimal value and suitable components. The basic operating principle of the modified



(a) (b)

Fig. 5. Simulation results of open circuit voltage in 1-stage modified Dickson charge pump with different capacitances. (a) Input signal is from the voltage generated on the (a) guard rail and (b) wooden beam.

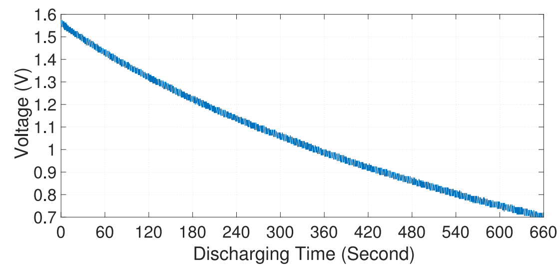


Fig. 6. Voltage across 100 μF capacitor versus discharging time.

Dickson charge pump is as follows: during the negative half-cycle, the voltage source charges capacitor C1 through diode D1 (see Fig. 2). In the coming positive half-cycle, diode D1 is reverse biased while diode D2 is forward biased, which conducts adding the voltage across C1 to the input voltage source. The total input charges up capacitor C2 to $V_{\text{negativepeak}} + V_{\text{positivepeak}}$. The regulation voltage, V_{reg}, and ripple voltage, V_{rip}, could be approximately expressed as [25]

$$V_{\text{reg}} = \frac{\left(n^3 + \frac{9n^2}{4} + \frac{n}{2}\right)I}{12fc} \tag{1}$$

$$V_{\text{rip}} = \frac{\left(n^2 + \frac{n}{2}\right)I}{8fc} \tag{2}$$

where n denotes the number of stages of the charge pump, I denotes the output current, f is the frequency of the source signal, and c is the capacitor value. From the equations, we can see that decreasing the capacitance affects both the regulation voltage and the ripple voltage. A capacitor with a small value discharges rapidly leading to a large fluctuation and significant output voltage drop. However, larger capacitance does not necessarily imply better performance since larger capacitors have a longer charging time and hence may need many cycles until they are charged. This is especially true in railway bridge scenarios, where the input signal has a weak amplitude, low frequency, and short duration. Therefore, the output voltage is not enough to close the load switch.

To determine the optimal capacitance for the rectifier, we study the voltage generated on the bridge. We select the electromagnetic ModelD device from ReVibe Energy to harvest vibration energy and convert it into electrical energy. We place it both on the guard rail and on the wooden beam. The output voltage is measured using an RIGOL MSO4014 digital oscilloscope. Then, the voltage data is imported into the Cadence PSPICE simulation tool as the input voltage to the 1-stage modified Dickson charge pump.

Fig. 5 shows the open circuit voltage with capacitor values of 10 nF, 0.1 μF, 4.7 μF, and 50 μF, respectively. The rising slope demonstrates the charging rate, and the falling slope is the discharging rate. The figure shows that 10 nF and 0.1 μF capacitors discharge sharply, which leads to a quick drop of the output voltage. When increasing the capacitance to 4.7 μF, the discharge speed is much slower reaching a high output voltage eventually. This is beneficial for storage capacitor of energy management to reach load switch threshold sharply.

However, when we increase the value to 50 μF, the output voltage is lower than with a capacitance of 4.7 μF. The reason is the weak and low frequency input signal that cannot quickly charge the 50 μF capacitor to a high voltage. On the other hand, the results are similar in both guard rail and wooden beam placements. We conclude that the suitable rectification capacitor is in the range between 4.7 μF and 50 μF. The result is then verified with real-world experiments.

D. Load Switch

Load switches provide a simple and efficient means for systems to power submodules on demand. They are widely used in power distribution, power sequencing, and state transition. In the EcoVibe system, the load switch connects and disconnects the power supply to the sensor node in accordance with the result of the event detector. The sensor node is completely switched off during the period of inactivity, which saves energy compared to being in sleep mode.

We choose a MOSFET as load switch, since it is a voltage-controlled device and has extremely high input resistance (order of magnitude of MΩ). These characteristics match well with the proposed event detector. On the one hand, the energy management unit in the event detector can directly control the load switch through a storage capacitor. Therefore, it does not need any additional electronic components (such as amplifier, comparator, or potentiometer) to generate an interrupt signal. On the other hand, the discharging time of the storage capacitor becomes extremely long due to the near infinite input impedance of the MOSFET. As a result, several μJ energy stored in the capacitor are able to keep the switch on for a long time. Based on the capacitor discharge equation [26], the time T_{on} during which the switch is in ON state can be calculated as follows:

$$T_{\text{on}} = -R_{\text{in}} C_{\text{storage}} \cdot \ln\left(\frac{V_{\text{th}}}{V_{\text{storage}}}\right) \tag{3}$$

where R_{in} and V_{th} are the input resistance and threshold value of the MOSFET, respectively. C_{storage} is the value of the storage capacitor and V_{storage} is the voltage across it. Assuming that a 100 μF storage capacitor is charged to 1 V by the vibration energy harvester, the threshold of the MOSFET is 0.7 V, and the input resistance is 10 MΩ, then T_{on} is

$$T_{\text{on}} = -10 \text{ M}\Omega \cdot 100\ \mu\text{F} \cdot \ln\left(\frac{0.7 \text{ V}}{1 \text{ V}}\right) = 356 \text{ s}. \tag{4}$$

To verify these results, we connect a 100 μF capacitor to the gate of a PMV16XN N-channel Trench MOSFET from

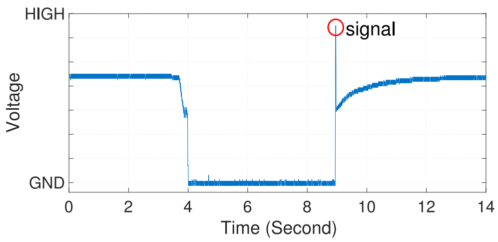


Fig. 7. Electric potential difference between GPIO and earth ground when the load switch opens, closes, and the sensor node sends a signal to turn off itself.

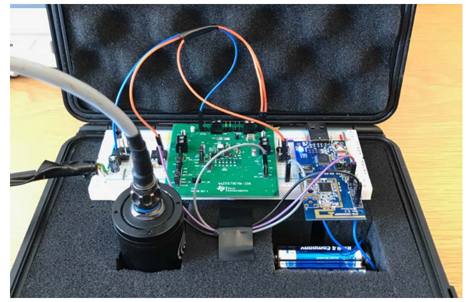


Fig. 8. Prototype implementation of the ECOVIBE system using commercially available off-the-shelf components.

Nexperia. The transistor is suitable for load switch applications because of its low threshold voltage and very fast switching speed. Fig. 6 shows the voltage across a 100 μF capacitor as the discharging time increases. It takes 11 min for the voltage to drop from 1.57 V to 0.7 V. If the crossing voltage is 1 V, the corresponding time to 0.7 V is 322 s. That means that 50 μJ energy ($W = (1/2)\mathrm{CV}^2$) is enough to activate the sensor node to work longer than 5 min.

E. Adaptive OFF Control Circuit

When turning on the MOSFET switch, the power supply rail is connected to the system, and the sensor node starts to sense the related bridge parameters such as vibrations, elastic waves, and local stresses. The raw measurements are then preliminary processed on the sensor node to reduce the data communication burden. After having transmitted the information, the sensor node goes idle. The total duration for the tasks is usually less than one minute. As demonstrated in Section III-D, the load switch can be closed for several minutes even with a small amount of energy. Hence, if two train crossings happen during a short time, there is a risk of missing an event in case the second train passes when the load switch opens. To avoid this problem, we design an adaptive OFF control circuit that opens the switch when the sensor node finishes its task.

A possible solution is to add a switch-controlled discharge path from the output of the event detector to ground. The control logic can be driven by one of the sensor's general purpose input output (GPIO) ports. However, we found that there exists a high voltage between GPIO and ground by default, because a low-side switching architecture is adopted in ECOVIBE. This should be eliminated so that the discharging path is open during the event detection period. A comparator has the ability to perform this task, but it is an active component that dissipates energy during the period of inactivity. This conflicts with our goal of minimizing energy waste. Another approach is to use an nMOS or pMOS-based high-side switching architecture to control the sensor node. However, the minimum turn-on voltage requirement for the load switch becomes the sum of power supply and the threshold of the load switch ($V_{\text{out}} > V_{\text{cc}} + V_{\text{th}}$) in an nMOS-based high-side switching architecture. A dc–dc boost charger is desired for increasing the output of the event detector to a high voltage, but it affects both the response time and the sensitivity of the event detector. pMOS-based high-side switching architectures have larger power consumption when the sensor node is turned on, since this solution requires an additional inverter circuit.

TABLE I
KEY COMPONENTS AND PARAMETERS

Component	Parameter
Harvester Resonance Frequency	42.2 Hz
Harvester Bandwidth	35.2 to 49.2 Hz
Rectifier Capacitor	4.7 μF
Rectifier Diode	Skyworks SMS7630
Storage Capacitor	100 μF
Load Switch	Nexperia PMV16XN
Solid State Relay	IXYS LBA110
Current Limiting Resistor	1 $k\Omega$

After many attempts, we found that both GPIO and analog ground of the sensor node have electric potential to earth ground, but there is no voltage between them when the load switch is open. When the load switch is closed, the analog ground of the sensor node connects to earth ground, and the voltage on the GPIO is 0 V. If the GPIO pin is set to high level, there is a high potential difference between GPIO and analog ground of the sensor node. Based on these observations, we choose a solid state relay as switch in an adaptive OFF control circuit. As shown in Fig. 2, the GPIO is connected to the positive control input and the analog ground of the sensor node is connected to the negative control input. The two normally open poles in the solid state relay are connected to the output of the event detector and earth ground, respectively. Fig. 7 depicts the voltage change behavior of the GPIO port. During the inactive periods before the fourth second, there is a high potential at the GPIO. When a train passes the bridge, the sensor node is activated and the potential jumps to zero. After finishing its tasks at the ninth second, the sensor node sends a control signal to quickly discharge the storage capacitor for powering itself down.

IV. PROTOTYPE IMPLEMENTATION

Fig. 8 shows ECOVIBE's prototype implementation, and the key parameters of selected components are listed in Table I. As event detection circuit we have selected the electromagnetic vibration energy harvester ModelD v2 from ReVibe Energy. The resonance frequency is 42.2 Hz, at which the maximum power output is 3.8 mW with 0.5g acceleration. It also has a reasonable power output in the frequency range from 35.2 to 49.2 Hz. Our rectifier is built using an SMS7630 Schottky diode since it has a low threshold voltage. The value of rectifier capacitor is 4.7 μF. We use TI's BQ25570 evaluation module for energy management. We tried to connect the output of the rectifier to the BQ25570's V_{in} and V_{out} pins to turn on the load switch. However, we found that it needs a long time period of vibrations to activate the V_{out} pin. The reason is that the main boost converter does not work until BQ25570's V_{stor} pin reaches 1.8 V. After that, there is voltage on the V_{out} pin. To address this issue, we directly connect the V_{stor} pin with the rectifier output and use the BQ25570's V_{bat} pin to trigger the load switch. Rather than attaching an extra storage element at the V_{bat} pin, we use the 100 μF ceramic capacitor after V_{bat} pin on the BQ25570 evaluation module to store vibration energy.

As load switch we use a Nexperia PMV16XN N-channel Trench MOSFET. The typical gate-source threshold voltage is 0.7 V, which helps to improve the sensitivity to detect passing trains. We use the Tmote Sky platform for sensing, data processing, and wireless communication. In order to adaptively turn off the load switch, we chose IXYS LBA110, a solid state relay of type normally open to quickly discharge the storage capacitor in the event detector. GPIO port 2 of the 6-pin expansion header in the sensor node connects to positive control, and the negative control is connected to the analog ground port of the 10 pin expansion header through a current limiting resistor. Note that the value of the resistor is important. An ill-suited resistor causes inadequate discharge and the sensor node would go into an unstable condition.

As discussed above, we implement EcoVibe using off-the-shelf components. In the following, we present the overall cost of our system.

The rectifier capacitor and rectifier diode cost \$0.21 and \$0.45, respectively. The MOSFET load switch costs \$0.33 and the solid state relay costs \$4.2. These costs are per-unit and quoted at quantity 10. The TI BQ25570 evaluation module is expensive at a cost of \$102.5. But the BQ25570 integrated circuit costs only \$6.9. To further reduce the cost of the energy management unit, a good substitute is using one P-channel MOSFET and a capacitor to store energy. This way, the cost of the energy management unit could be reduced below \$1. Commercial vibration energy harvesters are currently very expensive due to small batch manufacturing. We believe this cost will be reduced to a reasonable price with the development of micro-electro-mechanical system-scale vibration energy harvesters [27]. At that time, EcoVibe systems could be fabricated on a single chip at low cost and small size.

V. Energy Consumption

In this section, we compare EcoVibe's energy consumption to that of a state-of-the-art *trigger-based* system and an *ideal duty-cycled* system. We first provide models that we then populate with values from data sheets for a numerical comparison.

A. Energy Consumption Modeling

The system's operational states can be roughly divided into sleep and active states. In the sleep state the system is in a low-power mode waiting to be woken up to perform measurements and other tasks in the active state. The average power consumption $\bar{P}$ can then be written as in (5), where q is the fraction of time the system spends in active mode, i.e., its duty cycle

$$\bar{P} = (1-q)P_{\text{sleep}} + qP_{\text{active}}. \tag{5}$$

TABLE II
Power Consumption of COTS Components

Component	Mode	Consumption
CC2650	active (32 MHz)	P^{mcu}_{active}=6.8 mW
CC2650	sleep	P^{mcu}_{sleep}=2.8 μW
CC2650	deep-sleep	P^{mcu}_{deep}=0.42 μW
MPU9250	active	P^{accel}_{active}=1.26 mW
MPU9250	low-power (7.81 Hz)	P^{accel}_{low}=31 μW
MPU9250	deep-sleep	P^{accel}_{deep}=8 μW
MOSFET	off	$P^{mosfet}_{leakage}$=0.12 μW
MOSFET	on	P^{mosfet}_{loss}=0.28 μW

As mentioned in Section II, trigger-based systems rely on a secondary low-power system to wake up the primary system when events occur. In sleep periods, the secondary system is active, and the primary system can be set into deep-sleep mode, only able to wake up on external interrupts. Likewise, the secondary system can be set into deep-sleep mode in the active periods when the primary system performs its tasks. Thus, P_{active}, and P_{sleep} for a trigger-based system can be defined as

$$\begin{aligned} P^{\text{trigger}}_{\text{active}} &= P^{\text{mcu}}_{\text{active}} + P^{\text{secondary}}_{\text{deep}} + P^{\text{sensor}}_{\text{active}} \\ P^{\text{trigger}}_{\text{sleep}} &= P^{\text{mcu}}_{\text{deep}} + P^{\text{secondary}}_{\text{active}} + P^{\text{sensor}}_{\text{deep}}. \end{aligned} \tag{6}$$

Duty-cycled systems are scheduled to wake up periodically. In the sleep periods, the system is in low-power mode, where CPU and system clocks used by CPU and peripheral modules are disabled, while an auxiliary clock remains active. A timer interrupt wakes up the system and puts it into active mode. Thus, the power consumption for active and sleep periods for a duty-cycled system can generally be defined as in (7), where we assume that the sensor can be set into deep-sleep mode during sleep periods

$$\begin{aligned} P^{\text{dc}}_{\text{active}} &= P^{\text{mcu}}_{\text{active}} + P^{\text{sensor}}_{\text{active}} \\ P^{\text{dc}}_{\text{sleep}} &= P^{\text{mcu}}_{\text{sleep}} + P^{\text{sensor}}_{\text{deep}}. \end{aligned} \tag{7}$$

EcoVibe essentially constitutes a secondary system, but it does not consume energy in both sleep and active periods. It also allows the primary system to be completely turned off during sleep periods. There exists only a tiny leakage power consumption in sleep state due to the imperfect MOSFET transistor. During the system's active periods, there is a small conduction loss as a result of the load current (I), flowing through the MOSFET transistor. Thus, the energy consumption of EcoVibe can be defined as

$$\begin{aligned} P^{\text{EcoVibe}}_{\text{active}} &= P^{\text{mcu}}_{\text{active}} + I^2 R_{DS} + P^{\text{sensor}}_{\text{active}} \\ P^{\text{EcoVibe}}_{\text{sleep}} &= 0 + V_{\text{cc}} I_{\text{leakage}} + 0 \end{aligned} \tag{8}$$

where V_{cc} is the source voltage and I_{leakage} is the MOSFET's leakage current. R_{DS} is the MOSFET's drain–source on-state resistance. Existing off-the-shelf transistors (e.g., PMV16XN) have a drain–source on-state resistance in the mΩ level, and a drain leakage current much smaller than 1 μA.

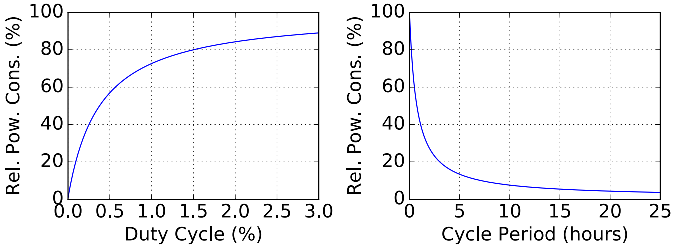


Fig. 9. Percentage of power consumed by ECOVIBE compared to trigger-based system. (Left): Percentage consumed as function of duty cycle. ECOVIBE requires less than 60% of trigger-based system's power when the systems are active 0.5% of the time. (Right): Percentage consumed as function of cycle period with 10 s active period. ECOVIBE requires less than 15% of trigger-based system's power, when active 10 s every five hours.

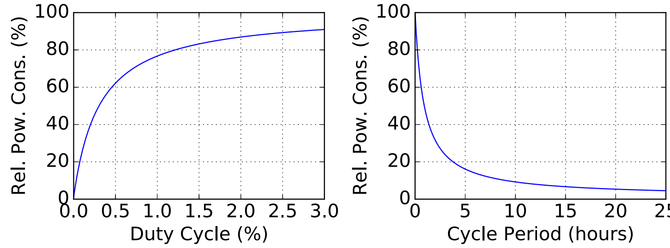


Fig. 10. Percentage of power consumed by ECOVIBE compared to the duty-cycled system. The duty-cycled system consumes less energy than the trigger-based system. Therefore, ECOVIBE's energy savings over the duty-cycled system are slightly lower than the savings over trigger-based system.

B. ECOVIBE *Versus Trigger-Based System*

Based on these energy models, we numerically compare the energy consumption of ECOVIBE to that of a trigger-based system composed of a Texas Instrument CC2650 SoC, and the InvenSense MPU9250 accelerometer. We select these since both are off-the-shelf, state-of-the art components with very low power consumption. We assume that ECOVIBE is composed of the same components for comparison purposes. The component's power consumption (at 2.8 V), obtained from the respective data sheet, are listed in Table II. In sleep periods, the trigger-based system keeps the MCU in deep sleep, and the accelerometer in low-power mode. In active periods, both MCU and accelerometer are kept active, for both ECOVIBE and the trigger-based system. ECOVIBE also consumes additional power due to the MOSFET in both active and sleep periods. We assume that the trigger-based system consumes no other power than that of the main components. Thus, the power consumption in both systems can be expressed as

$$\bar{P}_{\text{EcoVibe}} = (1-q)P^{\text{MOSFET}}_{\text{leakage}} + q\left(P^{\text{mcu}}_{\text{active}} + P^{\text{accel}}_{\text{active}} + P^{\text{MOSFET}}_{\text{loss}}\right) \tag{9}$$

$$\bar{P}_{\text{trigger}} = (1-q)\left(P^{\text{mcu}}_{\text{deep}} + P^{\text{accel}}_{\textit{low}}\right) + q\left(P^{\text{mcu}}_{\text{active}} + P^{\text{accel}}_{\text{active}}\right). \tag{10}$$

The left graph of Fig. 9 shows the relative power consumption $\bar{P}_{\text{EcoVibe}}/\bar{P}_{\text{trigger}}$ for different values of the duty cycle q. The figure shows that the duty cycle must be relatively low for ECOVIBE to significantly reduce the power consumption. This is because P_{active} is on the order of 1000 times greater than P_{sleep}, and will therefore dominate the power consumption for higher values of q. However, for a duty cycle lower than 0.5%, ECOVIBE consumes less than 60% of trigger-based system's power consumption. In our application, we need an active period of 10 s. A duty cycle of 0.5% implies that we can measure 10 s during a 34 min cycle period. In railway bridge applications even much longer sleep periods can be acceptable, e.g., measuring a single time per day. Although the system wakes up at every train pass, it can decide to immediately go back to sleep if the last measurement is too recent.

The right graph of Fig. 9 shows the relative power consumption for different cycle lengths with an active duration of 10 s. Measuring every 5 h, ECOVIBE consumes less than 15% of the power of the reference system, and less than 4% if measuring once a day. It should also be noted that the trigger-based system used here has a significantly lower power consumption during sleep periods (tens of μW) than that reported by SenetSHM [18] (a few mW). The energy savings resulting from using ECOVIBE compared to their system is therefore even greater than that shown in Fig. 9.

Fig. 11. Field test on target bridge. Passing trains are monitored by ECOVIBE. The event detector is placed on guard rail, wooden beam, and deck.

C. ECOVIBE *Versus Ideal Duty-Cycled System*

Now we compare the power consumption of ECOVIBE to that of a duty-cycled system. As previously mentioned, a duty-cycled system would most likely miss events and/or sample between them, and therefore provide a much lower quality of service compared to trigger-based system. We here assume that the exact times for events are known and focus only on the energy consumption. The power consumption of a duty-cycled system can be calculated as

$$\bar{P}_{\text{dc}} = (1-q)\left(P^{\text{mcu}}_{\text{sleep}} + P^{\text{accel}}_{\text{deep}}\right) + q\left(P^{\text{mcu}}_{\text{active}} + P^{\text{accel}}_{\text{active}}\right). \tag{11}$$

We compute the relative power consumption $\bar{P}_{\text{EcoVibe}}/\bar{P}_{\text{dc}}$. The results are very similar to those of the trigger-based system, but we show them in Fig. 10 for completeness. In conclusion, in applications with a low duty cycle ECOVIBE is significantly more power efficient than duty-cycled systems, even if one can predict the exact time for the next event to occur.

VI. FIELD TESTS

We conduct field tests with ECOVIBE on the old Lidingö bridge in Stockholm, Sweden. The bridge's total length is around 825 m, in which the longest span is 140 m and the shortest span is 14.3 m. As shown in Fig. 11, the bridge carries one railway track for commuter trains. The other half side

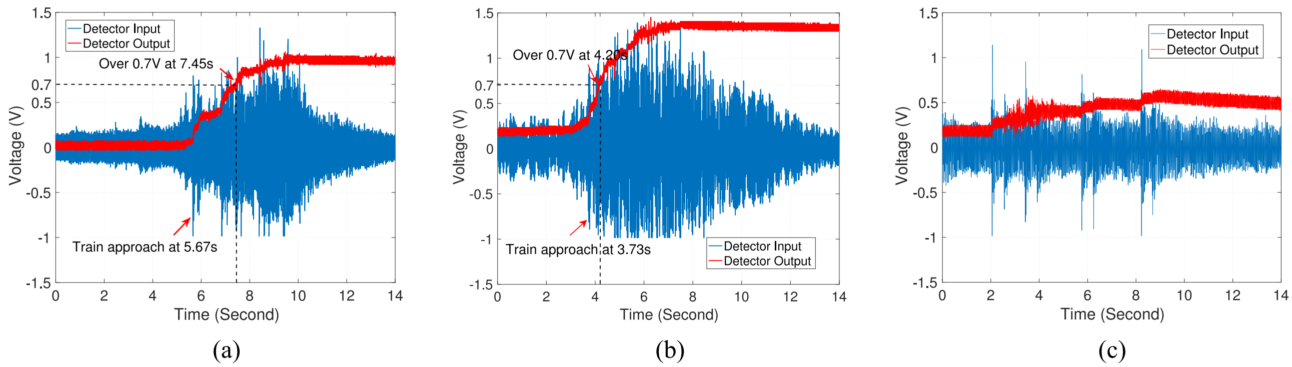


Fig. 12. Results of voltage generating from vibration energy harvester and output voltage of event detector at the three positions when a train passes by. (a) Guard rail. (b) Wooden beam. (c) Deck.

of the bridge is a walkway serving pedestrians, bicycles, and motorcycles. Cars are not allowed on the bridge.

A. Determining Harvester Location

The first question we face in the field deployment is "where should we place the vibration energy harvester for train detection?"

1) Setup: To answer the question, we place the vibration energy harvester at three different locations: 1) the guard rail; 2) wooden beam; and 3) yellow wooden deck. The input voltage (the voltage generated by the vibration harvester) and output voltage of the event detector are measured using an oscilloscope. From the maximum value of the output voltage, we can determine if a location is suitable. On the other hand, we can also estimate the startup delay by observing the time until the output voltage reaches the load switch's threshold.

2) Results: Fig. 12 shows the voltage generated by the vibration energy harvester and the output voltage of the event detector at the three positions when a train passes. The data is recorded for 14 s. Fig. 12(a) and (b) shows that when a train approaches, the voltage generated by the vibration energy harvester increases significantly. The energy is then used as input to the charge storage capacitor through the rectifier and the energy management unit. The peak voltage across the capacitor reaches 1 V when the harvester is on the guard rail and 1.4 V when it is on the wooden beam. In both cases the harvester is able to turn on the load switch for several minutes, which is enough for the sensor node to finish all its tasks.

The placement on the wooden deck next to the railway track is not as successful as the other two positions. As Fig. 12(c) shows, the peak voltage is only 0.6 V which is below the activation voltage of 0.7 V. Although this location is closer to the track, the vibrations are not strong enough to charge the capacitor to the threshold voltage of the MOSFET switch. One reason is that the harvester is only loosely attached to the deck since attaching it more firmly would have required to stop all train traffic on the bridge. On the guard rail, we exploit the harvester's magnetism to attach it to the rail. The harvester is also attached well to the wooden beam with the help of the upper beam.

The voltage trace also illustrates the startup delay, i.e., the time needed to harvest sufficient energy for the wake-up system to reach the activation voltage of 0.7 V. Fig. 12(a) shows that sufficient energy to reach the activation threshold is collected in 1.78 s (from second 5.67 to 7.45) after the first train axis has passed the harvester. The startup delay is only 0.47 s (from second 3.73 to 4.20) in Fig. 12(b) since the vibrations are much stronger for this harvester placement.

After the wake-up voltage has been generated, a monitoring sensor system will have some further start-up delays. A standard accelerometer which is used on the popular SensorTag platform, KXTJ9-1007, has a power-up time of 10 ms, plus a varying startup time depending on the sample rate. The typical delay for a sample rate of 50 Hz is 21 ms, but the worst case startup delay can be as high as 650 ms [28]. Other newer accelerometer chips, such as the MPU9250, offer faster total startup times but still in the order of tens of ms. Other involved device components—MCU and bus initialization—have delays that are order of magnitudes smaller and will only marginally add to the total startup delay.

For our target scenarios, the sensing should be activated in less than 1.9 s in order to start measuring while the train is still passing the sensor. This value is determined by train length and its speed. With a suitable harvester placement, this is feasible even when taking worst case accelerometer startup delays into account. Thus, monitoring scenarios with strain gauges and accelerometers are both possible with EcoVibe.

3) Insights: The vibration intensity varies at different locations on the bridge when a train passes, so the performance of EcoVibe is affected by harvester's placement. The stronger the vibration intensity is, the faster the sensor node turns on. From an engineering point of view, the harvester should be tightly attached on the bridge to get more vibration input. Then, the sensor node is able to start measuring quickly and collect more structural health information. Another possible method is to put the harvester some meters ahead of the node. Although the startup delay is long sometimes (such as 1.78 s), the sensor node could meet the passing train timely. From a research point of view, low threshold voltage load switch devices and high efficiency vibration energy harvesting

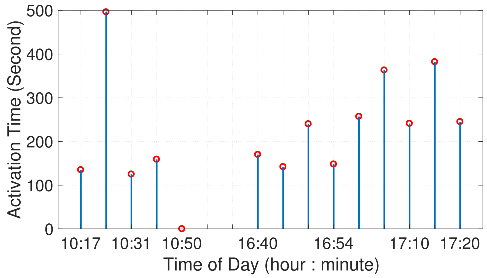


Fig. 13. Successful detection and corresponding activation time on a weekday.

technologies are two research directions to improve system performance.

B. Detection and Activation Time

To better understand the system performance, we decide to measure two metrics: 1) detection rate and 2) activation time. Detection rate is detected train crossings versus actual train crossings. Activation time is the duration that the load switch is turned on when a train is detected.

1) Setup: We test ECOVIBE on a weekday. The vibration energy harvester is placed on the guard rail in the morning and changed to the wooden beam in the afternoon. The LED lights are set to blink when the node is active. In order to measure the activation time, the adaptive OFF control function is disabled. We manually turn off the sensor node if it still works before the next train passes. The total blink time of the sensor node's LED is manually recorded as activation time.

2) Results: Fig. 13 shows that five commuter trains are present on the bridge from 10:15 to 11:00. During rush hour between 16:35 and 17:25, nine trains pass by. ECOVIBE successfully detects all the events except the train at 10:50. In this particular case, the train slows down very much presumably since we are around the sensor node box and observe the train and node. The low speed decreases the vibration strength significantly and leads to reduced vibration energy.

The corresponding activation time is also shown in Fig. 13. Most of the activation times are around 150 s in the morning from 10:15 to 11:00 except the one that reaches 496 s when a train passes at 10:20. On the other hand, the activation times in the morning are smaller than in the afternoon. One reason is that the train speed during rush hour in the afternoon is much higher than in the morning. Another reason is that the weight of trains during rush hour is probably much larger than the trains in the morning since there are more people on these trains. Therefore, both speed and weight of the train affect the activation time. When a sensor node is triggered by a train between 16:50 and 17:20, it keeps working even until the next train is about to across the bridge. We thus regard the time interval between two trains as activation time. We believe that the actual activation time would be much longer than the interval between two trains.

3) Insights: The condition of trains has an impact on detection rate and activation time. A passing train with slow speed generates weaker vibrations compared to one with higher speed. The total weight of a train also affects the induced vibration intensity. In rush hours, ECOVIBE is able to detect passing trains fast, and has longer activation times than it does in off-peak hours. Although the event detector can only harvest small amounts of energy from slow speed trains with light weight, it is able to close the load switch and the corresponding activation time is enough for the sensor nodes to finish all sensing and communication tasks.

VII. CONCLUSION

In this paper, we present the design, prototype implementation, and evaluation of ECOVIBE, an on-demand sensing system for railway bridge health monitoring. A passive event detection circuit is designed to continuously monitor crossing trains without any power consumption. A MOSFET-based switch activates a sensor node for a long time using little energy. We have also designed an adaptive logical control circuit that powers off a sensor node as soon as it has finished all its tasks. Using an energy consumption model, we show that ECOVIBE is more energy-efficient than state-of-the-art trigger-based systems and ideal duty-cycled systems. Field tests on our target bridge show that ECOVIBE successfully detects passing trains and that the activation times are long enough to finish sampling, data processing, and wireless communication. We also believe that the working principle behind ECOVIBE is feasible in other event-driven applications, such as intrusion detection, smart roads, and data mule sensor networks.

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