Quasi-self-powered Infrastructural Internet of Things: The Mackinac Bridge Case Study

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ABSTRACT

Autonomous, continuous and long-term monitoring systems are required to prognosticate failures in civil infrastructures due to material fatigue or extreme events like earthquakes. While current battery-powered wireless sensors can evaluate the condition of the structure at a given instant of time, they require frequent replacement of batteries due to the need for continuous or frequent sampling. On the other hand, self-powered sensors can continuously monitor the structural condition without the need for any maintenance; however, the scarcity of harvested power limits the range at which the sensors could be wirelessly interrogated. In this paper, we propose a quasi-self-powered sensor that combines the benefits of self-powered sensing and with the benefits of battery-powered wireless transmission. By optimizing both of the functionalities, a complete sensor system can be designed that can continuously operate between the structure's maintenance life-cycles and can be wirelessly interrogated at distances that obviates the need for taking the structure out-of-service. As a case study, in this paper we present the design considerations involved in prototyping quasi-self-powered sensors for deployment on the Mackinac Bridge in northern Michigan, with a target operational life span greater than 20 years.

CCS CONCEPTS

• **Hardware → Application-specific VLSI designs**; **Full-custom circuits**; **Hardware test**; • **Computer systems organization →** *Embedded and cyber-physical systems*; • **Applied computing →** Physical sciences and engineering;

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KEYWORDS

Piezo-Floating-Gate Sensor; Quasi-self-powered; Infrastructural Internet of Things; Structural Health Monitoring

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1 INTRODUCTION

With growth of the world economy and its population, there is an ever increasing dependency on larger and more complex networks of civil infrastructure as evident in the billions of dollars spent by federal, state and local governments to upgrade or repair transportation systems and utilities. Despite these large expenditures, the nation continues to suffer staggering consequences from infrastructural decay. According to the American Society of Civil Engineers 2017 Infrastructure Report Card, the overall health of America's infrastructure is at a D+ grade, with bridges and roads at C+ and D, respectively [30]. As part of the solution, they recognize the cost and difficulty of using, maintaining, and improving the nation's infrastructure; further, they note the importance of supporting research into innovative new technologies, such as structural health monitoring (SHM) to expedite repairs or replacement, and to promote cost savings. Due to the forces of nature that act on infrastructure, it is impossible to have a complete understanding of how these structures will act in deployment conditions; therefore, a method for sensing the state of these structures periodically is necessary. Currently, the primary method of determining the health of infrastructure is visual inspection, resulting in a mostly qualitative assessment of damage [1–3]. In contrast to this qualitative methodology, several quantitative methods are also employed, such as the measurement of structural damage through the use of electrical impedance [19] and ground penetrating radar [4].

However, in order to provide a more expansive method of sensing, several groups have proposed a method of structural monitoring through the use of wireless sensor networks (WSNs). Advantages of this approach are many, as they are relatively low cost and

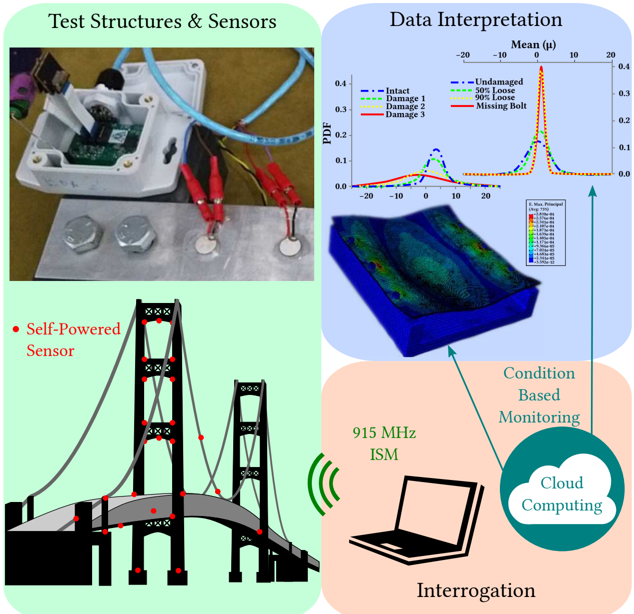

Figure 1: Vision of infrastructural Internet of Things (*i*-IoT).

provide a wide swath of coverage over a majority of the structure. In addition, these sensor nodes have a relatively low cost of installation and require a relatively low amount of maintenance [29]. These sensor networks collect several types of relevant structural data such as acceleration, stress, load, and vibration [29]. Yet even these methodologies are limited, as they frequently use battery powered instruments for sensing as well as the transmission of data; the method of obtaining power and the life of external power supply continues to be the bottleneck in the design of these WSN for the purpose of SHM [29]. On the other end of the spectrum are self-powered SHM systems [13, 31] that require zero-maintenance (no replacement of batteries) and can continuously operate over the useful life-span of the structure without experiencing any down-time. The self-powered sensors have been the basis of our ongoing work in the area of infrastructural Internet of Things (*i*-IoT), which uses a widespread network of self-powered sensing devices with the ability to monitor the impact and strain that are applied to structures.

The goal of the *i*-IoT framework, as shown in Fig. 1, is to provide a robust methodology that can easily deploy on a variety of different structures without compromising or interfering with the integrity of that structure. However, a key aspect of the *i*-IoT framework is ability to collect data from an array of self-powered sensors embedded inside a structure, without taking the structure out-of-service. Self-powered operation is limited in its ability to wirelessly transmit the stored data over long distances due to high energy requirements. Therefore, in this paper we are proposing a quasi-self-powered sensing system that combines the benefits of self-powered sensors that are continuously active and battery-powered transmitters that are sporadically active. The combination of the two techniques results in ultra-low average power consumption of the entire system implying that they can be deployed on real-world structures for a long periods of time with relatively low amounts of maintenance. In this paper we present a case study of a quasi-self-powered SHM sensor that has been designed for deployment on the Mackinac Bridge in northern Michigan, which is one of the largest suspension bridges in North America.

2 PFG SENSING PRINCIPLE

Over the last decade our research group has investigated an alternate approach for designing SHM sensors, which are powered directly by the sensing signal itself [18], which for an SHM application are mechanical strain and the mechanical acceleration. If a sensor could self-power itself from the energy latent in the strain-variations and in the mechanical acceleration, then the device can continuously monitor for events of interest without experiencing any down-time. The challenge is that less than a microwatt of power is available when the sensor is embedded inside a structure like concrete [14, 16]. At this power-level it is practically impossible to implement a continuous monitoring system comprising of energy converters, energy regulators, analog-to-digital converters, signal processors and wireless transceivers. Also, given that SHM sensors have to be operational for more than 20 years, raw strain-measurements cannot be stored due to the limitations on the silicon area and the instantaneous measurements cannot be transmitted wirelessly due to limitations on In [11, 12, 15, 25, 28] we reported a piezo-floating-gate (PFG) sensing technique that self-powers by harvesting energy from micro-strain variations.

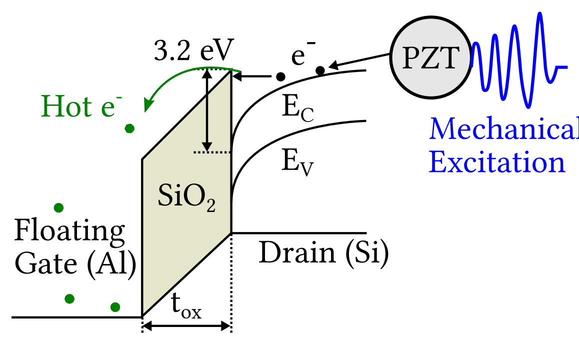

Figure 2: Simplified principle of PFG operation.

The principle of the PFG sensor is illustrated in Fig. 2 where a piezoelectric transducer (in this case a lead zirconate titanate, or PZT) harvests energy from mechanical strain variations to generate high-energy electrons (or hot-electrons) in the channel of a MOSFET transistor. When the energy of some of these electrons (with the right momentum vector) exceeds the energy barrier (3.2 eV) of the silicon, silicon-di-oxide interface (as shown in Fig. 2), these electrons surmount the barrier and get trapped onto a floating-gate. Because the floating-gate is electrically isolated by a high quality insulating oxide, the injected electrons remain trapped for a long period of time. As the piezoelectric transducer is periodically excited, more electrons are injected onto the floating-gate and the cumulative charge stored on the floating gate is a function of the duration and the magnitude of the mechanical excitation. This approach directly couples the physics of piezoelectric energy harvesting with the physics of hot-electron injection to sense, compute and store mechanical usage statistics and hence can be used to push the fundamental limits of self-powered sensing of mechanical strain. The floating-gate also serves as a non-volatile storage memory from which the mechanical usage data could be retrieved at a later stage for offline analysis. This leads to a "sense-now, analyze-later" paradigm which has been the basis of several PFG based sensors [17, 23, 24, 27, 32, 33]. The difference between the respective PFG sensor designs is the interface circuit that connects the piezoelectric transducer with the floating-gate memory. By modifying the topology of the injector interface circuit, the sensor can also be designed to record different statistics of the strain signal, like strain-levels [24, 32], strain-rates [23], or time of occurence [34].

3 EXPERIMENTAL VERIFICATION

We demonstrated the efficacy of our proposed monitoring methods with an experimental that consists of a steel plate under an in-plane tension load. The steel plate under consideration is notched in the middle to introduce damage, as shown in Fig. 3, with the notch in the vertical direction to give better control over the crack size under uniaxial tensile loading; a deviation in the notch location or direction would not significantly alter the results using the methodology proposed by [22]. The damaged segment is surrounded by PZT transducers affixed to the surface of the steel plate, in turn, the transducers are connected to our self-powered PFG sensors that will log the cumulative strain experienced by the transducer. As the damage grows in the steel plate, the strain experienced by each transducer increases near the crack tip of the notch — since the sensors are continuously logging the statistics of this strain, it becomes possible to periodically collect data from the sensors and still deduce the damage progression [5, 9, 10, 20–22].

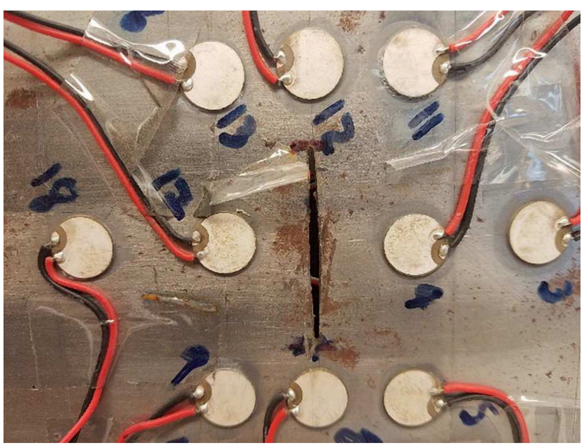

Figure 3: In-lab testing of a steel plate with controlled damage, surrounded by several piezoelectric transducers [22].

For verification purposes, the number of sensors is more than required, in practice, one could use a finite element simulation to predetermine segments of the structure that are more susceptible to damage and prioritize the placement of sensors accordingly. Even with modeling, it is exceedingly difficult to select an optimal sensor placement a priori since the type of damage is unknown. Therefor, a sensor fusion strategy was developed to improve the detection performance using spatial measurements, this "group effect" strategy has been reported in [5, 21]. Even if the location of damage is not known in advance, the group effect can be utilized for condition-based monitoring.

The performance of the self-powered PFG sensor has been experimentally validated on other laboratory test-beds, with a sampling of results given in the Data Interpretation block of Fig. 1. The top left portion of the figure shows results from detection of a bottom up crack in asphalt concrete pavement [20], the top right shows the detection of localized failures such as the loosening of a bolt [6], and the bottom illustrates a simulation verifying the data interpretation [5].

4 MACKINAC BRIDGE SENSOR DESIGN

The PFG sensor was fabricated through MOSIS as a system-on-chip that includes all necessary components (the piezoelectric transducer notwithstanding) for self-powered sensing and data logging. The PFG core and pad ring requires $1.5 \times 1.5\,\text{mm}^2$ as shown in Fig. 4, and relevant characteristics are listed in Table 1.

Table 1: Fabricated PFG Characteristics

CMOS Process	OnSemi 0.5 µm
Chip Size	$1.5 \times 1.5\,\text{mm}^2$
Minimum Energy (Self-powered)	100 nJ
Supply Voltage (Readout)	1.8 V
Power Dissipation (Readout)	75 µW
Programming Resolution	> 12 bits

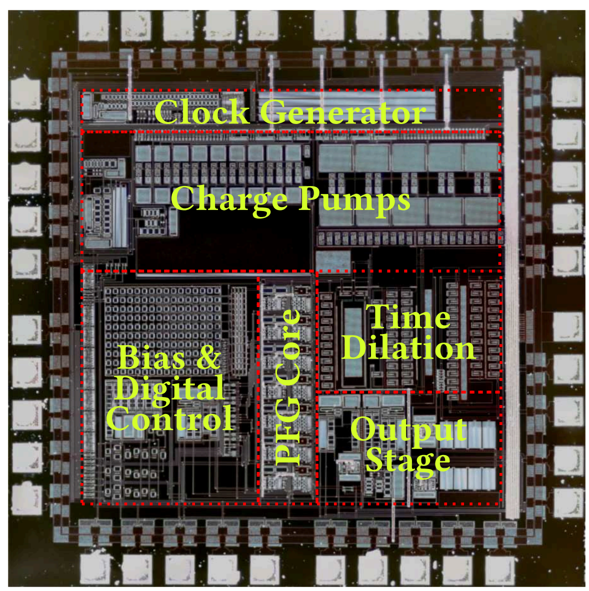

Figure 4: Die micrograph of the $1.5 \times 1.5\,\text{mm}^2$ chip.

4.1 Design Considerations

4.1.1 Analog to Digital Conversion. As evident in the chip micrograph of Fig. 4, die space is at a premium when designing the SoC to fit on a MOSIS tiny core (note that some areas of the die that appear empty are filled with passive resistors). In the pursuit of maintaining a reduced design complexity, some design choices were made that will require consideration when taking the chip outside of a controlled lab environment. The first such consideration is the use of a pulse encoder ADC in lieu of a more robust conversion method to interface the PFG's stored charge to external digital devices. The pulse encoder output frequency as a function of the input voltage (i.e. Floating-Gate Voltage), is presented as Fig. 5, which highlights the non-monotonic behavior of the ADC. In the initial state, the floating-gate voltage would be high, and as the sensor experiences mechanical excitation the injected electrons will reduce the voltage output, thus increasing the output frequency. At an inflection point near 470 mV, this trend reverses as the discharge branch of the ADC becomes too weak to respond in a timely fashion. By observing the duty cycle of the output pulse train, as presented in the bottom trace of Fig. 5, we can decode the floating-gate voltage even though the output frequency is not monotonic.

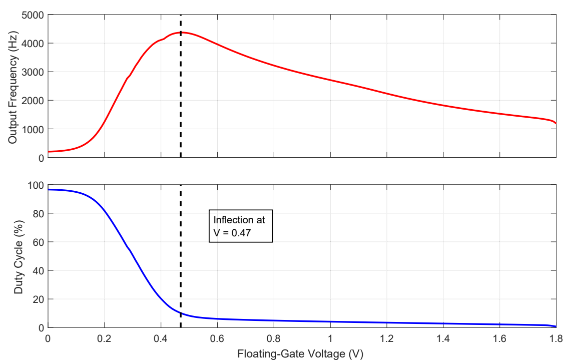

Figure 5: Simulation showing (top) frequency as a function of input voltage, and (bottom) duty cycle of same.

4.1.2 Voltage Reference. Another aspect to consider is the temperature dependence of the self-biased current source used for generating on-chip voltage biases. In simulation, one will observe a large deviation in the output frequency of the pulse encoder as a function of temperatures we'd expect at the Mackinac Bridge installation site, as shown in Fig. 6.

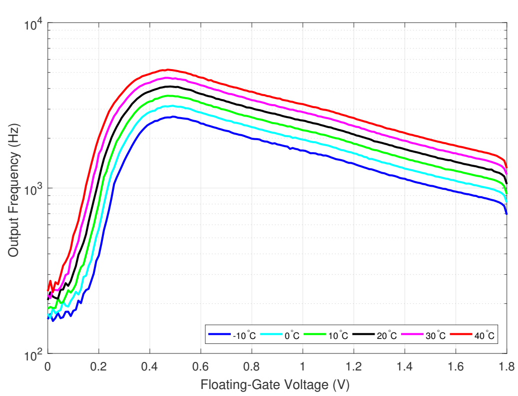

Figure 6: Simulation of pulse encoder output frequency when sweeping the input voltage and ambient temperature.

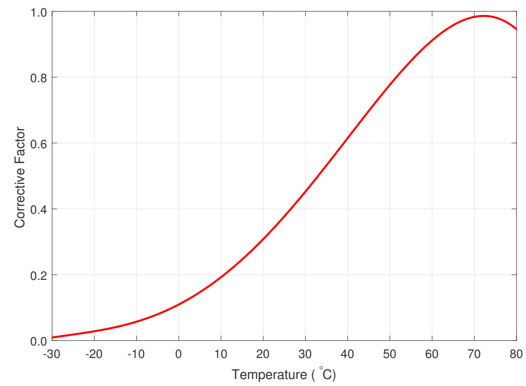

Figure 7: Corrective factor for temperature effects.

To account for the temperature effect, we developed a corrective factor as illustrated in Fig. 7. This factor was derived from averaging the response of three fabricated chips that were initialized to an output frequency of 1.15 kHz at lab room temperature of 21.5 °C and subjected to temperatures from −30 °C to 80 °C in a climate chamber. The data in subsequent discussions are processed using the appropriate corrective factor considering the observed ambient air temperature during data collection and are thus presented as unitless.

5 FIELD TEST

5.1 System Enclosure

We previously demonstrated a backscatter RF interface for data retreival [13, 24], yet in the case of communication in the dense steel structure of the Mackinac Bridge, for long ranges, they are not feasible. Thus, we opted to swap out the backscatter interrogation unit with an active Radio Frequency (RF) link – leading to a quasi-self-powered platform since the continuous sensing is self-powered, but the interrogation is not [9]. A preliminary feasibility test using a short-term deployment on the Mackinac Bridge [8] was successfully completed and we miniaturized the design to make a more robust platform for an active RF interface, as shown in Fig. 8. Note that modules `b` & `f` are self-powered for continuous monitoring, the remaining modules only power up for sporadic RF communications.

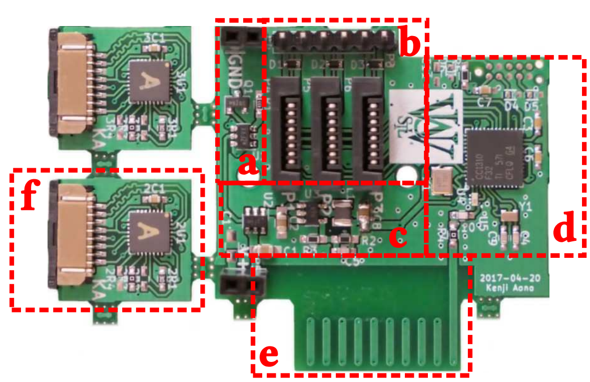

Figure 8: PCB for: (a) timer; (b) piezo input; (c) battery management; (d) micro-controller; (e) antenna; (f) PFG module.

An assembled board with sensors and battery mounted in a weatherproof enclosure is shown in the top left of Fig. 1, operational details of the system are listed in Table 2. To take advantage of the quasi-self-powered architecture, an ultra-deep sleep mode that draw less than 50 nA from the battery (≈35 nA for the TPL5111 from Texas Instruments and another ≈15 nA leakage through bypass capacitors) is enabled by Fig. 8(a), this module places the active portion of the system into a non-responsive deep sleep mode for 300 s at a time, before waking up the micro-controller (MCU). Upon wakeup, the MCU will idle while waiting for a command, if a read command is detected it will pull the data from the PFG sensors, else it goes back to sleep. The PFG sensor modules (Fig. 8(f)) are connected using a Flag Flexible Cable(Fig. 8(b)), which allows for easy swapping in and out of the sensors depending on application. Similarly, (Fig. 8(b)) allows for the piezo transducers to be swapped. In the case of the Mackinac Bridge, the sensors are configured for measuring upwards of two million loading cycles of mechanical strain [10]. (Fig. 8(c)) takes the ≈3 V supplied by ½AA Lithium Thionyl Chloride Cells from Tadiran to 1.8 V to power the MCU (Fig. 8(d)) and RF communication through the integrated antenna (Fig. 8(e)). RF communication is enabled by a Texas Instruments CC1310 using a proprietary protocol on the 915 MHz band.

Table 2: System Enclosure Specification

Enclosure Size	$59 \times 94 \times 35\,\text{mm}^3$
Sensors per Enclosure	3
Radio Band	915 MHz ISM
Transmit Power	up to 10 dBm
Transmit Distance	>100 m
Transmit Current	2.5 mA
Transmit Time (Max)	13.5 s
Receive Sensitivity	−112 dBm
Receive Current	225 µA
Receive Time (Max)	6 s
Sleep Current	50 nA
Sleep Duration	300 s

From the specifications in Table 2, we can estimate average current consumption when there is no request for data (no energy spend on RF transmission) and for when there is a request as:

$$\begin{aligned}\text{Request} &= \frac{I_{\text{on}}t_{\text{on}} + I_{\text{search}}t_{\text{search}} + I_{\text{off}}t_{\text{off}}}{t_{\text{on}} + t_{\text{search}} + t_{\text{off}}} \\ &= \frac{2.5\,\text{m}\cdot 13.5 + 225\,\mu\cdot 6 + 50\,\text{n}\cdot 300}{13.5 + 6 + 300} < 110\,\mu\text{A} \\ \text{No request} &= \frac{I_{\text{search}}t_{\text{search}} + I_{\text{off}}t_{\text{off}}}{t_{\text{search}} + t_{\text{off}}} \\ &= \frac{225\,\mu\cdot 6 + 50\,\text{n}\cdot 300}{6 + 300} < 5\,\mu\text{A}\end{aligned}$$

Working under the assumption that commands are sent only 1% of the time (that is, approximately two or three readings a day), and incorporating an 85% derating factor on the battery, a single ½ AA battery with 1.2 Ah capacity would last:

$$1.2\,\text{Ah} \div (0.99\cdot 5\,\mu + 0.01\cdot 110\,\mu)\ \text{A}\cdot 0.85\cdot\left(\frac{1\,\text{yr}}{8766\,\text{h}}\right) \approx 20\ \text{years}.$$

Once the battery lasts 20 years, other components (weatherproof seals, capacitors, PZT, etc.) may begin to fail before the system enclosure requires a battery change. In this way, the quasi-self-powered system presents a viable method for developing an *i*-IoT framework by leveraging self-powered sensors to move the system bottleneck away from battery technology.

5.2 Mackinac Measurements

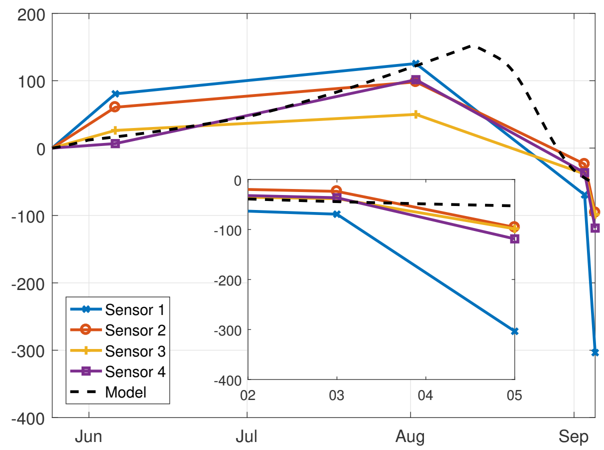

Figure 9: Data from four sensors, dashed black line shows expected results from model. Inset showing before and after Labor Day (Sep 04).

The data collected between May 25th and September 5th of 2017 are presented in Fig. 9 after having the corrective factors applied. Sensors 1 through 3 are at the same installation site and show the same trend in data logging, with some difference in peak frequency as well as injection rate due to fabrication mismatch. Sensor 4 was on a different installation site, but had a similar configuration in terms of PZT size (see Fig. 10 for the types of locations under consideration) and PFG tuning parameters. The sparse data collection appears to follow the trend that we expected based on the PFG characterizations from in-lab testing [7, 10, 17, 26, 34] and the traffic statistics of the Mackinac Bridge. The trend line is shown as the dashed black. The inset of Fig 9 shows the data collected before and after the Mackinac Bridge Labor Day Walk (on Sep. 4th), which drew a crowd of over 25,000 people, much greater than usual traffic on the bridge. It shows that during the event the sensors logged

Figure 10: Mackinac Bridge used for deployment study.

a much larger amount of data than it had in the days before. The deviation from the model trace, which is based on monthly traffic statistics, highlights the extra strain that the Labor Day Walk placed on the sensors. Note that we are only showing a unit-less, corrective-factor-applied frequency output of a single channel from each PFG sensor, from which a layperson may have trouble extracting any meaningful information.

6 CONCLUSIONS

In this paper we presented a system level design of a quasi-self-powered sensor that combined the benefits of continuously active self-powered sensors with sporadically active wireless transmission. The paper also presented a design case study where the sensor was prototyped for field deployment on the Mackinac Bridge in northern Michigan. The prototype was designed to continuously operate over a duration of 20 years and with a transmission range greater than 100 m. Our preliminary deployment results and measured data show the sensors to be functional over a period of a few months. An introspection into the information gleaned from the data will appear in forthcoming publications.

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