CapHarvester: A Stick-on Capacitive Energy Harvester Using Stray Electric Field from AC Power Lines

MANOJ GULATI[*], IIIT-Delhi, India
FARSHID SALEMI PARIZI[†], University of Washington, USA
ERIC WHITMIRE, University of Washington, USA
SIDHANT GUPTA, Microsoft Research, USA
SHOBHA SUNDAR RAM, IIIT-Delhi, India
AMARJEET SINGH, IIIT-Delhi, India
SHWETAK N. PATEL, University of Washington, USA

Fig. 1. CapHarvester harvests energy from AC power liens without an ohmic connection individual conductors or the ground. CapHarvester works on fully-insulated and bundled AC cables. Shown are three real-world applications being powered by the CapHarvester. ApplianceTag allows detection of the appliance state, on or off, for sustainability applications (left); HeatMap sensors are scattered around a building to measure ambient temperature and build a zone by zone temperature map (center); and FarmCheck measures environmental parameters such as temperature, humidity and light intensity for indoor farming applications (right).

Internet of Things (IoT) applications and platforms are becoming increasingly prevalent. Alongside this growth of smart devices comes added costs for deployment, maintenance, and the need to manage power consumption so as to reduce recurrent costs of replacing batteries. To alleviate recurrent battery replacement and maintenance, we propose a novel battery-free, stick-on capacitive energy harvester that harvests the stray electric field generated around AC power lines (110 V/230 V)

[*]Corresponding author
[†]Co-primary student author

Authors' addresses: Manoj Gulati, IIIT-Delhi, New Delhi, India, manojg@iiitd.ac.in; Farshid Salemi Parizi, University of Washington, Seattle, WA, USA, farshid@uw.edu; Eric Whitmire, University of Washington, Seattle, WA, USA, emwhit@cs.washington.edu; Sidhant Gupta, Microsoft Research, Redmond, WA, USA, sidhant@microsoft.com; Shobha Sundar Ram, IIIT-Delhi, New Delhi, India, shobha@iiitd.ac.in; Amarjeet Singh, IIIT-Delhi, New Delhi, India, amarjeet@iiitd.ac.in; Shwetak N. Patel, University of Washington, Seattle, WA, USA, shwetak@cs.washington.edu.

2474-9567/2018/9-ART110 $15.00
https://doi.org/10.1145/3264920

without an ohmic connection to earth ground reference, thereby obviating the need for cumbersome scraping of paint on concrete walls or digging a earth ground plate. Furthermore, our harvester does not require any appliance or load to be operating on the power line and can continuously harvest power after deployment. In effect, end-users are expected to simply stick the proposed harvester onto any existing power-line cord in order to power a sensing platform. Our controlled lab measurements and real-world deployments demonstrate that our device can harvest 270.6 µJ of energy from a 14 cm long interface in 12 min. We also demonstrate several applications, such as distributed temperature monitoring, appliance state monitoring, and environmental parameter logging for indoor farming.

CCS Concepts: • **Hardware → Sensor devices and platforms**; *Sensor applications and deployments*; Reusable energy storage; • **Human-centered computing** → *Ubiquitous computing*;

Additional Key Words and Phrases: Power harvesting, Internet of Things, Ultra-low power

ACM Reference Format:
Manoj Gulati, Farshid Salemi Parizi, Eric Whitmire, Sidhant Gupta, Shobha Sundar Ram, Amarjeet Singh, and Shwetak N. Patel. 2018. CapHarvester: A Stick-on Capacitive Energy Harvester Using Stray Electric Field from AC Power Lines . *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3, Article 110 (September 2018), 20 pages. https://doi.org/10.1145/3264920

1 INTRODUCTION

According to the 2017 forecasts by Gartner Inc, a total of 20.4 billion IoT devices will be connected to the Internet by 2020[1]. These devices demand frequent battery replacement, adding to overall deployment and maintenance costs. As the number of connected devices continues to grow, the need for scalable power management poses a major concern. Reducing power consumption could allow small batteries to stay active for a year or two instead of months. However, keeping track of these batteries is still a tedious task. Self-powered sensor nodes have emerged as a possible solution to the problem. These nodes can harvest energy from the ambient environment in the form of light[19], temperature [14, 17, 19, 24], vibration [10, 20], RF [13, 21], and Wi-Fi [18]. Based on the availability of these ambient signals, each solution has its own benefits and constraints [16].

In this paper, we propose a novel battery-free, stick-on capacitive energy harvester that harvests energy from stray electric fields around the ubiquitous AC power lines. Although prior preliminary work has explored harvesting energy from power lines [8, 9], these solutions have traditionally required a direct ohmic connection to ground — that is, the harvester requires an end-user to run a wire from each of the harvester devices to earth ground (achieved in prior art by connecting to a copper plate inside a wall). In contrast, our solution relies on capacitive coupling to ground, enabling easier and safer end-user deployment and use in many more scenarios, where a direct ground connection is not feasible. For instance, attics can have long insulated runs of electrical cabling with no easy access to earth ground, except at junction boxes. Although advantageous, designing a harvester without this ohmic ground connection poses a significantly more challenging problem.

To address this challenge, we use stacked capacitive electrodes to provide a local ground and design our device to effectively harvest from this nanowatt source — a significant contribution of this work. Power lines are ubiquitous inside buildings, thus facilitating a broad range of applications like monitoring ambient temperature, detecting building occupancy, monitoring appliance usage for optimizing energy consumption, environmental sensing for indoor vertical farming applications, and water leakage detection. All of these applications can be enabled with our battery-free wireless device, which is capable of periodically transmitting collected sensor data over an RF channel to a base station.

Unlike prior work [2, 4, 6], our harvester can clamp on to any *fully bundled and insulated* AC power line without intercepting individual conductors (phase, neutral, and earth) and can harvest continuously without any active appliance operating on these power lines. This is a notable contribution and improvement over the commonly used electromagnetic harvesters that require: (a) the user to access and clamp onto individual

[1]https://www.gartner.com/newsroom/id/3598917

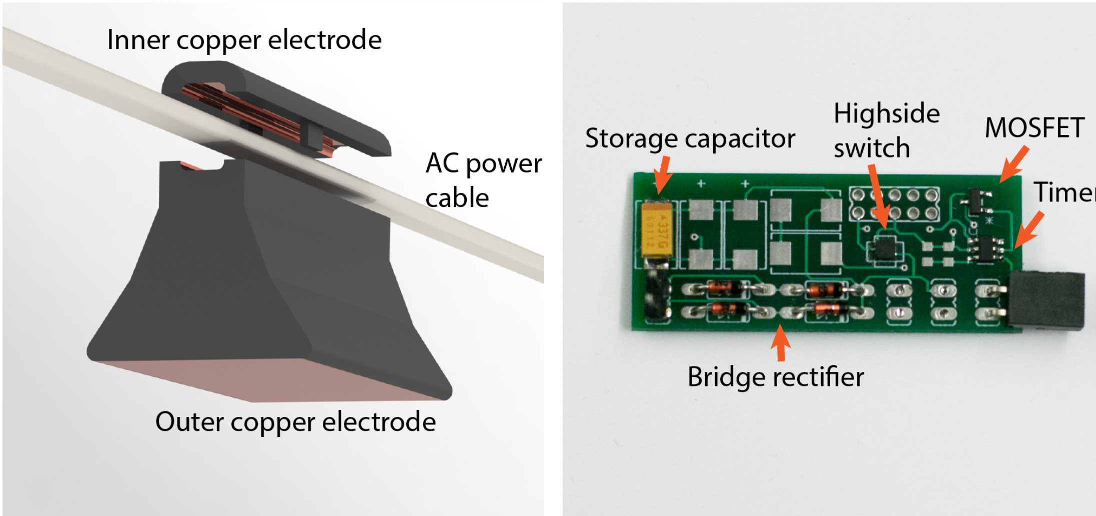

Fig. 2. (a) The CapHarvester (capacitive energy harvester) clamps on to a low-voltage power cable and harvests power without current flow. (b) Our power harvesting circuitry rectifies the capacitively coupled 60 Hz power line signal and stores energy in a capacitor with low leakage current. A high side switch, timer, and MOSFET added to the power management circuit control the attached peripherals.

conductors so that the two directions of current does not produce a null field); and (b) a device on the tapped conductor be consuming current in order to create a magnetic field around the wire. These requirements are obviated with CapHarvester's capacitive coupling approach, which results in a safer, more convenient device. Our measurements in controlled lab settings and real-world environments demonstrate that we can harvest up to 270 µJ in 12 min using a 14 cm-long harvester deployed at 10 cm above ground.

In summary, the contributions of this paper are:

(1) A novel stick-on capacitive energy harvester that harvests the stray electric fields from AC power lines with no need for access to ohmic earth ground thus providing increased safety and ease of use.
(2) A characterization of the energy harvesting capabilities of our device in various environments and with different power cables, as well as an analysis of the trade offs in the design of the device's geometry.
(3) Three real-world representative applications of this device, including distributed temperature sensing for HVAC control, non-intrusive appliance state (on/off) sensing, and environmental sensing for indoor farming.

This manuscript is organized as follow. In Section 2, covers the related work of CapHarvester. In section 3, we explain the theory of operation of stray electric field harvesting and the principles behind the double-layer stacked capacitor model proposed in this work. Section 4 presents important hardware design considerations, including component selection, materials, and electrode placement. In Section 5, we characterize the energy harvesting capabilities of the proposed harvester. Section 6 discusses the design space needed for end users to employ this harvester. Section 7 discusses some of the applications where this harvester can be deployed in real-world scenarios. Section 8 and section 9 covers the discussion and conclusion of this work.

2 RELATED WORK

The tradeoff between battery life and communication range is one of the foremost concerns in IoT technology [1, 7]. Extending communication range requires that devices increase their transmission power, leading to quicker battery drainage. Although people have proposed ultra-low power sensors and MCUs with on-chip wireless support, batteries are still the major bottleneck for power-intensive sensing. Furthermore, keeping track of the battery level in widespread, dense deployments is a major hassle.

In response, energy harvesting from the ambient environment has been explored as an alternative to battery-powered IoT. A number of different of energy sources have been leveraged, including light [19], temperature [14, 17, 19, 24], vibration [10, 20], RF [13, 21], and Wi-Fi [18]. Non-invasive energy harvesting from AC power lines, as in our work, has not been explored as thoroughly as other techniques.

In 2011, Gupta et al. explored using stray electromagnetic fields from power lines for low duty cycle sensing applications [6]. However, this work requires a large transformer placed in between conductors, which is not feasible for most applications due to space constraints. In 2013, DeBruin proposed a smart meter which uses two current transformers: one for harvesting energy to power the sensing circuit, and another for taking power measurements; this approach does not require an AC-DC transformer[4]. Campbell et al. proposed a self-powered circuit-level current meter [2] that uses two split core current transformers, and Moon et al. proposed Vampire, which has a custom toroid-based harvester [11]. The latter three devices can be clamped onto any current-carrying conductor for harvesting local magnetic fields and measuring power consumption. The major limitation of these works is that they require isolated phase and neutral conductors for installation. This is possible for some applications, but not in general for everyday use.

Another line of work has explored a low-profile power meter which connects with a 3-pin plug point for measuring the power consumption of appliances [5]. It harvests energy without making any ohmic connection with actual conductors, enabling a new dimension of plug load metering. However, this harvester design is specific to power cables that have plug points; again, it does not work for general applications.

Harvesting stray electric fields from AC power lines through capacitive coupling is an exciting approach as it can continuously harvest energy and does not require any appliance to be active on the power line. However, most of the exploration in this space is limited to power lines with a high voltage overhead [12, 22, 23].

In this work, we capacitively couple a stray electric field harvester with low voltage AC power lines; these power lines typically carry 110 V (North America) or 230 V (Asia Pacific) AC voltage at 60 Hz and 50 Hz respectively. Although this concept is not novel [3, 8, 9], prior work required an ohmic connection to earth ground for each harvester. In a building with painted walls, an ohmic connection requires scraping the paint off of the walls or digging a copper plate to get an earth contact, as Kim and Kong et al. demonstrate [8, 9]. This is undesirable for ubiquitous, end-user deployable sensors. Our harvester design addresses this challenge by using stacked electrodes to generate local reference ground and leveraging an optimized power management circuit to efficiently harvest stray electric fields.

3 THEORY OF OPERATION: STRAY ELECTRIC FIELD HARVESTER

In this work, we propose a novel capacitive energy harvester using stray electric fields from low-voltage AC power lines for energy harvesting.

Whenever an alternating voltage signal is fed through a power line (single-wire or multi-wire topology), a corresponding alternating electric field is generated on the outer surface of the cable. The strength of this field varies depending on the magnitude of the voltage signal and the dielectric constant of the shielding across the power line's conductors. Figure 3 illustrates the working principle for the capacitive energy harvester. C_{pp} represents the primary capacitive coupling between the outer surface of the power line and the phase conductor carrying a 110 V AC signal. C_{pp} serves as the driving source for an alternating electric field on the surface.

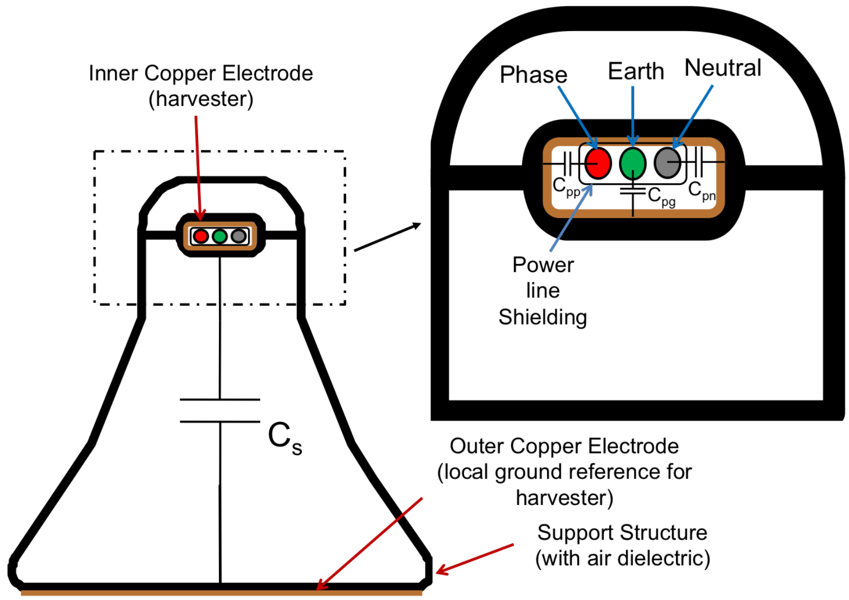

Fig. 3. Cross-sectional model of a power line having three conductors (phase, neutral, and earth). Each conductor has a primary capacitance (C_{pp}, C_{pn} and C_{pg}) with respect to the inner electrode and a secondary capacitance (C_s) exists between the inner and outer electrodes of harvester.

The other two conductors present in a multi-wire topology, neutral and ground, are tied to earth ground at the distribution side of the transformer. The capacitances corresponding to these two conductors, denoted as C_{pn} and C_{pg}, do not contribute any electric field.

Techniques for conventional electric field harvesting depend on the type of power line in question. For the high-voltage (HV) power lines found in industrial settings, a copper plate placed at some distance provides access to stray electric fields. For low-voltage (LV) power lines in residential and office settings, copper tape around the power line suffices. However, there are certain technical constraints that restrict the application of conventional techniques, particularly for the LV power lines we are interested in leveraging for harvesting. One of the foremost challenges is the availability of the earth ground to act as a reference. Earth ground can be accessed outdoors for HV power lines by digging a pit in the ground for a connection; for LV power lines, however, accessing earth ground requires concrete walls that lead directly to it or cumbersome infrastructure alterations to do so [3, 9]. Secondly, weak capacitive coupling limits the output power available at the harvester electrodes (a couple of volts with <1 μA of current). Typically, this capacitive coupling is weak since the voltage supply fed to the LV power lines is weaker (~100-300 V) in comparison to HV power lines (~11-33 kV); the coupled signal for LV power lines will be proportionally lower (i.e., a few volts per cm length of electrode). Also, capacitive coupling depends on the frequency of the signal and dielectric material. Coupling is weaker in most applications due to lower power signal frequencies (50 Hz or 60 Hz) and the presence of insulation material that lowers the dielectric constant of the power cables for shielding. Furthermore, in the absence of a reference to earth ground, energy harvesting becomes non-trivial and the amount of energy available at the output of the electrodes reduces significantly since in this case we are trying to harvest energy from a voltage source with a really high impedance. In order to analyze the available power with local reference ground, we characterize the power harvesting capabilities of our

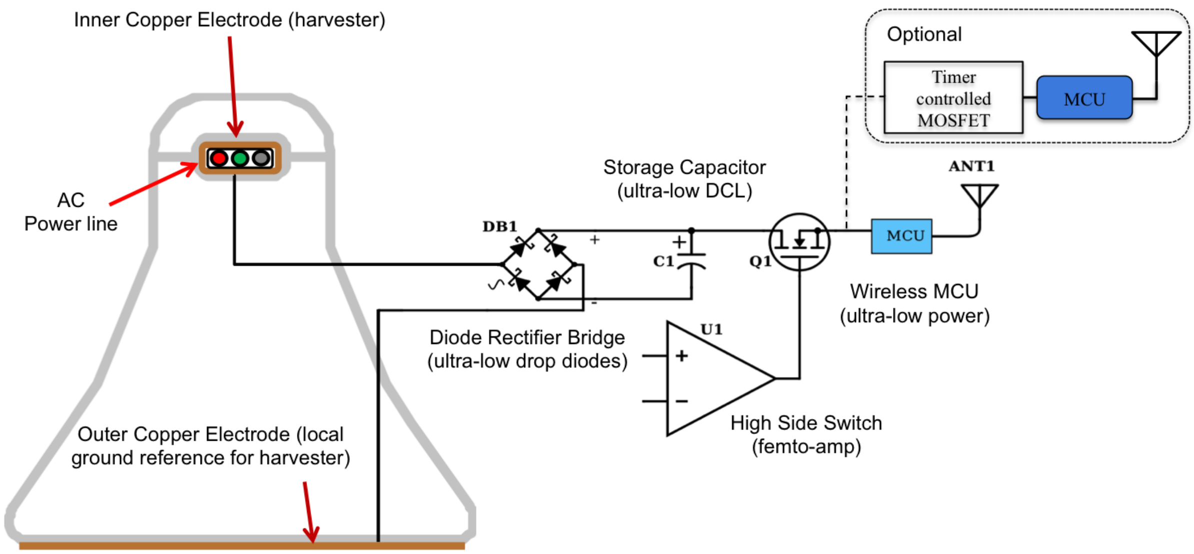

Fig. 4. The block diagram of our system, which consists of double-layer stacked capacitive electrodes, a diode rectifier bridge, a storage capacitor, a high side switch, and a wireless MCU for sensing applications. Optionally we also add a timer controlleed MOSFET circuit to drive wireless MCU for continuous and event based sensing applications.

device in various environments and with different power cables. We also analyze the tradeoffs in the design of harvester. These findings are discussed in detail in Section 5 and Section 6.

In order to harvest energy from ubiquitous LV power lines in a continuous manner, we propose a double-layer stacked capacitor model for capacitive energy harvesting. Our approach does not require a solid earth ground for reference and generates its own reference ground. Furthermore, our approach can effectively harvest power as little as nanowatts using ultra-low power harvesting circuit.

4 HARDWARE DESIGN

We propose a design for a capacitive energy harvester with five main components: capacitive electrodes, a diode rectifier bridge, a storage capacitor, a high-side switch, and a wireless MCU. Figure 4 illustrates the block diagram of the entire system and the different sections of the harvester. Before discussing the remaining blocks, we describe the double-layer stacked capacitor model of the harvesting electrodes since it is one of the most critical design choices required for the harvester.

4.1 Double-layer Stacked Capacitor Model of Electrodes

In order to remove the requirement of a reference earth ground, we propose a double-layer stacked capacitor model for the harvesting electrodes. Figure 3 shows the primary and the secondary layer of the stacked harvester model. Primary capacitance (C_{pp}, C_{pn} and C_{pg}) exists between the power line conductors (phase, neutral and ground) and the inner electrode made up of copper tape having contact with the outer surface of the power line. The inner electrode serves as the high potential electrode in our case. In order to generate a local reference ground that can serve a lower potential than the inner electrode, we add another layer of conductive electrodes made of copper tape[2], which is propped up by a 3D-printed support structure (Figure 4). Ideally, the secondary capacitance between the inner and the outer electrodes (C_s) should be as low as possible. Air, with a dielectric constant of ~1, is the primary dielectric between the inner and the outer electrodes. The area and separation of these capacitive electrodes are critical design parameters since they directly determine the voltage and power available at the output of these electrodes. In order to understand this relationship, we characterize variations in harvested power from different lengths and electrode spacings. These measurements are discussed in Section 5 (Analysis). Our design decisions and component selections are motivated by this power characterization. Some of these design parameters are variable and can be adjusted depending on the nature of the application. We discuss this strategic power management in more detail in Section 6 (Design Space).

4.2 Diode Rectifier Bridge

The AC voltage output from the capacitive electrodes is fed to a diode rectifier bridge consisting of small signal Schottky diodes for AC-DC conversion. Small signal Schottky diodes with ultra-low forward voltage drop are widely used in harvesting applications; however, most of them are designed to operate at fixed frequencies. In this system, we choose Vishay BAT85S diodes, which have a forward voltage drop (V_f) of around 100 mV (I_f=1 µA) at 60 Hz. The choice of a rectifier bridge over a full-wave rectifier is due to the fact that the latter requires an earth ground reference, which restricts the application space of this harvesting technique. As our harvester is designed for low frequencies (50 Hz or 60 Hz), we are not concerned about the parasitic capacitance that arises from diode leads.

4.3 Storage Capacitor

After AC-DC conversion, the output of the rectifier bridge is fed to a storage capacitor. The choice of capacitor depends highly on its DC leakage (DCL) and equivalent series resistance (ESR). The dielectric material of a capacitor is an imperfect insulator that allows a small amount of current to flow between the two conductive plates which is called the DCL. Electrolytic capacitors have large leakage currents while plastic, ceramic and tantalum capacitors have very small leakage currents. The storage capacitor should have as little DCL and ESR as possible in order to harvest effectively from a nano-watt source.

We choose AVX TAJ (AVX TAJD477K004RNJ)[3] series tantalum capacitors for this reason. The maximum DCL for this capacitor is 18.8 µA. We have to note that this number is reported at the rated voltage, which is 4 volts at 80 °C. Since our system is operating at much lower temperature and voltage the DCL will reduce significantly. The other benefit of this capacitor is it's low ESR(around 0.9 Ω).

Along with the dimensions of the harvesting electrodes, the ideal value of the storage capacitor also varies depending on application's requirement. Continuous sensing applications may require a bigger capacitor (~1-10 mF), but a sparse sensing application like temperature sensing can work with a smaller capacitor (~220 µF to 330 µF). The data rate at which the sensing system can communicate also depends on the size of the capacitor. We discuss capacitor selection in detail under strategic power management in Section 6 (Design Space).

4.4 Charge Controller (High-side Load Switch)

Like typical energy harvesting systems, our setup also requires a charge-controller that can switch output loads once the harvested energy reaches a certain threshold. There are several integrated solutions for this purpose, such as Texas Instruments BQ25570, Ablic (Seiko) S8823, and Linear Technology LTC3108. These solutions use dual-stage boost and buck converters or multi-stage charge pumps. However, none of them can be employed in

[2]Both the inner and outer electrodes are built using copper foil tape (3M 45J589) with a thickness of 3.50 mm, wrapped on the inner and outer surface of the support structure

[3]http://www.avx.com/products/tantalum/smd-tantalum-mno2/taj-series/

this system as they require a cold-start. A cold-start consumes a few milliamperes of current to turn on the primary boost converter/charge pump or a quiescent current (I_q) of ~1 µA, making them impractical for our harvester. Note that some of these charge controllers can perform a cold-start from a secondary storage cell or battery, but we strive towards a battery-free harvester. In order to control the output load in a hysteric manner, we explored N-MOSFET-based high-side switches. These switches drain quiescent current on the order of microamperes to facilitate the bias voltage requirements for the gate-source voltage (V_{gs}). To overcome this high drain quiescent current, we use the nano-watt high-side load switch from Semtech (TS12001-C018). This load switch has an on-state current of 70 nA and and off-state quiescent current of 100 pA. It also has a factory-programmed threshold voltage (V_{th}) for a comparator and does not require any external bias voltage like conventional N-MOSFET-based switches[4]. This high-side switch turns the output on when the storage capacitor hits V_{th}+500 mV and lets it discharge down to V_{th}, giving it a hysteric window of 500 mV. The storage capacitor is always harvesting charge, even when the high-side switch is closed); depending on the size of electrodes, though, it takes variable amounts of time to charge up to V_{th} again.

4.5 Wireless MCU

During the on-state, the high-side switch powers up an ultra low-power (ULP) wireless MCU (Texas Instruments CC1350) for approximately 20 ms. All the sensing and data communication tasks are handled by this MCU. We prefer the CC1350 wireless MCU over other MCUs as it supports long-range sub-GHz band (f_c=868 MHz) communication with an integrated ULP MCU (Active Tx consumes ~11mA at 1.95 V). It also supports a proprietary 15.4-Stack for sub-GHz band communication.

4.6 Charge Controller for Continuous Sensing (Nano-power Timer-based MOSFET Driver)

We also explore a continuous sensing application where we periodically turn on an ULP MCU MSP430FR5959 using a nano-power timer (Texas Instruments TPL5110) and a P-MOSFET (Infineon IRLML6402), sample the ADC, and write these values to the MCU's FRAM. The timer and MOSFET are connected to the output of the high-side switch and the gate of the MOSFET is controlled with the timer. The choice of the MOSFET is very important since it needs to have extremely low on resistance. This benefit, combined with the fast switching speed and small leakage current enables continuous sensing for CapHarvester. After a known interval (12-24 hours), the data that has been stored in the FRAM can be transmitted using a low-power transmitter.

Apart from these design considerations, application specific design variations are discussed in Section 7 (Application Space).

5 ANALYSIS: HARVESTER SPECIFICATIONS AND EFFICIENCY

Like most energy harvesting systems, the CapHarvester operates in a duty-cycled fashion, charging a storage capacitor up to a maximum voltage (2.21 V) before activating. As shown in Figure 5, the system remains active until the capacitor voltage falls to a lower threshold (V_{th} = 1.8 V).

Because our device relies on a local ground generated by an electrode, the performance strongly depends on the electrical environment in which it is placed. In the following sections, we investigate the impact of an ohmic ground connection, explore diverse environmental effects, and characterize our device performance with different power cables.

5.1 Methodology

In the following experiments, we measure the energy harvested by our device by measuring the voltage across the storage capacitor over time. For most of our proposed applications, we use a high-side switch that remains

[4]https://www.digikey.com/en/maker/blogs/introduction-to-high-side-load-switches/9324fe174d494b9e82f733fc23884050

active from $V_{th} = 1.8\,V$ to $V_{init} = 2.21\,V$. To enable a meaningful comparison, we report harvesting performance as the time it takes the capacitor to charge from 1.8 V to 2.21 V. We also report the average power, P, harvested during this time, t, according to Equation 1.

$$P = \frac{\left(V_{init}^2 - V_{th}^2\right) C_{\text{store}}}{2t} \tag{1}$$

Our measurement setup consists of a National Instruments (NI) USB 6003 data-acquisition (DAQ) unit configured for taking analog measurements in fully differential mode [-10 V to 10 V] at a sampling rate (F_s) of 10 kHz. We chose NI USB DAQ over a conventional digital storage oscilloscope (DSO) as the latter has a much lower input impedance (in range of tens of MΩs) and can significantly load a nano-watt source like a capacitive harvester by consuming few milliamperes of current. Also, most DSO's do not allow differential measurements without referencing to earth ground. NI USB DAQ has an input impedance of >10 GΩ, consuming <1 nA for taking each measurement and allows differential measurements without referencing to earth ground. Because the available power is so little, even this device with its high input impedance has a significant impact on the charge time. Rather than leave it connected to the circuitry, we periodically connect it to sample the voltage across the storage capacitor. We use Python (PyDAQMx, SciPy and NumPy) for configuring, logging, and filtering data from the DAQ.

5.2 Environment

Because our device relies on capacitive coupling to ground, it is essential to characterize its performance in a variety of locations. We tested the device in 11 locations. Table 1 summarizes the performance in these locations. Charge time is reported using a 4 cm high and 14 cm long electrode with a 330 μF storage capacitor.

These results show that performance is best when our device has a good coupling to the earth's ground. For example when tested on a concrete floor which has a good coupling to ground the charge time of CapHarvester was only 277 second on average. When placed on wooden surfaces, or When elevated off the ground, the charge

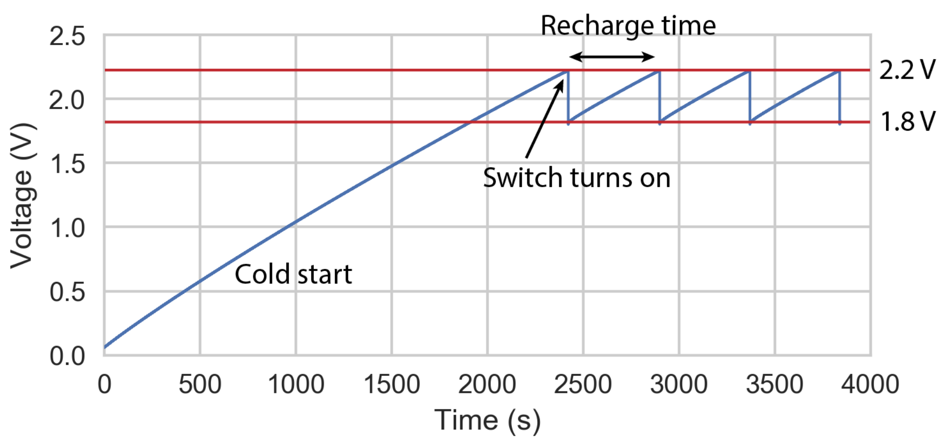

Fig. 5. When first installed, the harvester begins its cold start period. Once the storage capacitor reaches the trigger voltage of the high-side switch (2.21 V here), the switch activates and the device becomes active until the voltage drops to the lower cutoff voltage (1.8 V here). After that the recharge time of the device is significantly reduced.

Table 1. Charge time and average power harvested using CapHarvester in various locations in the US (110V/60Hz)

ID	Location	Surface	Charge Time (s)	Average Power (uW)
A	Ground floor of cement office building	Tile floor	277	0.95
B	Fifth floor of cement office building	Carpet	731	0.36
C	Second floor of wooden house	Carpet	1308	0.20
D	Outdoors	Concrete	242	1.09
E	Wooden Stud	Wood	780	0.34
F	Wooden Attic	Wood	2356	0.11
G	Wooden floor	Wood	2500	0.11
H	Residential Basement	Carpet	653	0.40
I	Table in Residential Basement	Wood	617	0.43
J	Residential garage	Epoxy Coating	267	0.99
K	Fifth floor of a cement lab rotary building	Epoxy Coating	467	0.57

time increases significantly. In the 11 locations we tested, we observed power harvesting rates that varied by a factor of 5x - 10x. We note that this technique will not work when suspended in free air, placed on drywall, or placed on a wooden table with poor coupling to ground. This poor coupling is mostly due to lack of conducting medium between the outer electrode of CapHarvester and the earth ground. Construction materials with a higher value of the dielectric constant can serve as a better coupling medium for capacitive energy harvester in comparison to materials with lower dielectric constant (good dielectrics) like dry air or vacuum. Hence the materials like wooden table and drywall act as a non-conductive medium (good dielectrics) and offer poor coupling to earth ground.

5.3 Power Cable

We also characterized the amount of power harvested from different cables using a 14 cm long and 4 cm high CapHarvester. We picked five commonly used cables (of different gauge, round/flat and lengths) and also calculated the average power delivered to CapHarvester. As shown in the table the charge time and the amount of power delivered to capacitive harvester varied significantly even for cables having a similar gauge, this is due to different capacitive coupling offered by these cables due to the variable length of outer shielding, inner conductors, and nature of dielectric used for shielding. In the future, a regression model can also be proposed which can help in estimating power delivered by a particular type (length, gauge, dielectric shielding) of power cable.

Table 2. The available output power with different types of extension cords arranged in the order of increasing charge time. The electrode had a fixed length (14cm) and with a local reference ground.

ID	Cable Type and Make	Gauge	Length (ft)	Power Rating(W)	Charge Time (s)	Average Power (uW)
A	HDX (SPT-2)	16	12	1625	443	0.595
B	Aurum (Outdoor/Indoor)	16	15	1625	707	0.373
C	Inermatic Table top	14	2	1250	1030	0.256
D	Hanvex-HAX10G	16	10	1250	1070	0.247
E	HDX (Outdoor/Indoor)	16	50	1625	1500	0.176

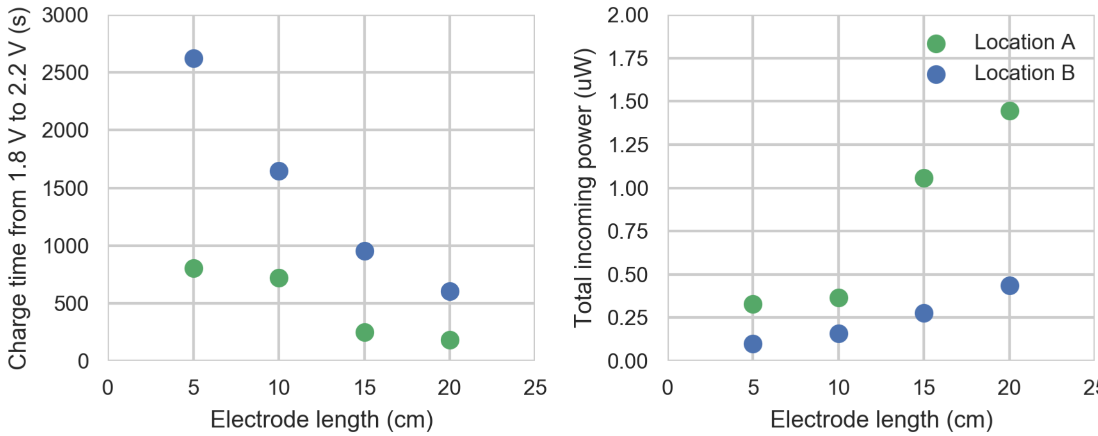

Fig. 6. Charge time and incoming power for different lengths of electrode.

6 DESIGN SPACE: EMPLOYING THE CAPACITIVE ENERGY HARVESTER

In this section, we first discuss the power management strategies for different applications that we demonstrate in this work. We then discuss the design considerations for these applications, which can also be used as a reference by future designers and inventors for other applications where this capacitive harvester can be employed.

6.1 Strategies for Power Management

We separate the application space for capacitive harvesting into two broad categories depending on the nature of the sensing involved. We discuss the strategies for power management that we employ for these categories and then their suggested hardware design configurations.

- **Sparse Sensing:** These are scenarios when data does not need to be delivered at a specific time. Examples of scenarios in this category include distributed temperature sensing, appliance state monitoring, and sensing environmental parameters for indoor farming. For most of these applications, we use a fixed length (14 cm) and spacing (4 cm) between electrodes for ease of deployment and vary the size of the storage capacitor depending on the energy budget required for sensing and data transmission. We also occasionally include a high-side switch with a higher threshold voltage.
- **Continuous- and Event-based Sensing**: Applications like pressure monitoring in industrial scenarios require continuous sensing for data logging and reporting anomalous events. This cannot be facilitated through a high-side switch-based charge controller as it will drive the load depending on a fixed turn-on voltage. However, continuous sensing applications require an uninterrupted supply of energy after a fixed time interval. To enable such applications, we employ an optional timer-based load driver that can be connected to the output of the high-side switch. This programmable timer can periodically drive a load for a known duration and can be turned off through an external control signal. Event-based sensing can be enabled by adding an additional firmware constraint on top of continuous sensing to transmit data whenever an anomalous event occurs or a predefined threshold is met. The size of the storage capacitor will vary depending on the energy requirements for continuous sensing and the data transmission rate.

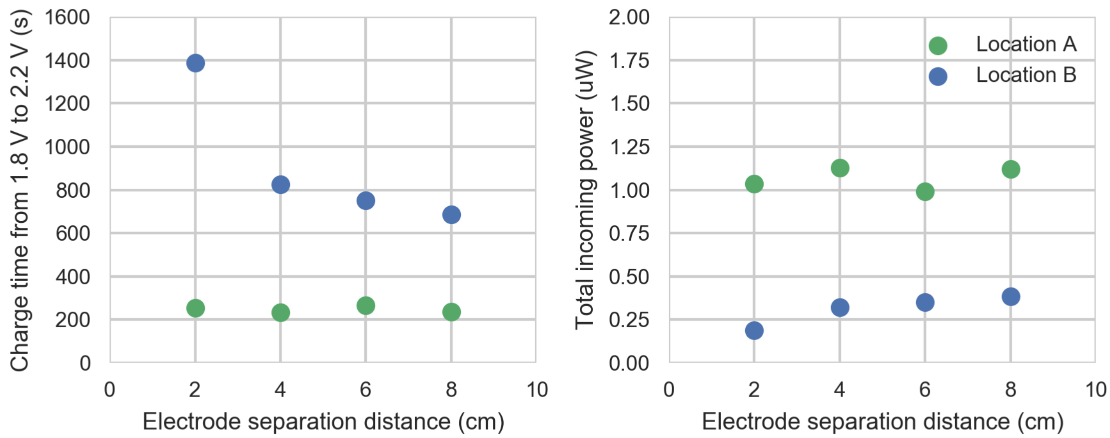

Fig. 7. Charge time and incoming power for different separation distances between the two electrode

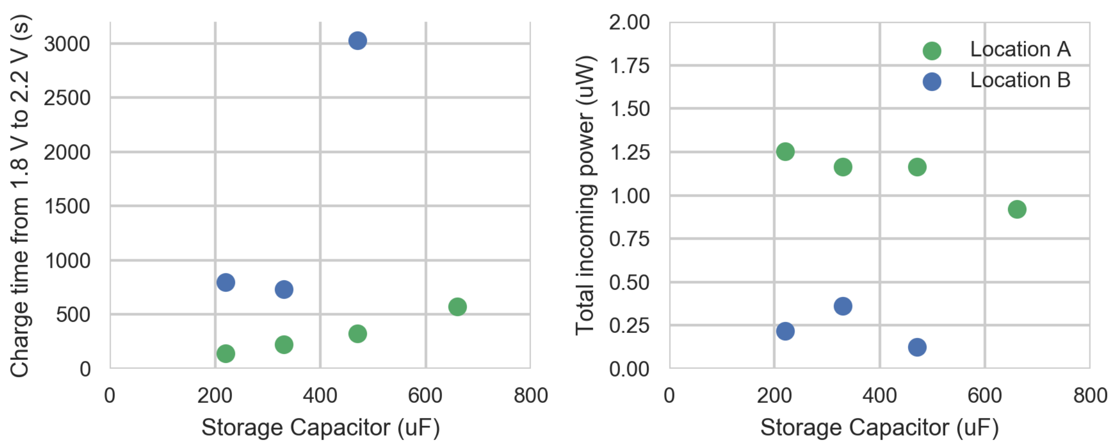

Fig. 8. Charge time and incoming power for different capacitors size

6.2 Design Space

In total, there are three major design variables: the length and spacing of capacitive electrodes, the size of the storage capacitor, and the configuration of the high-side switch or charge control circuit.

6.2.1 Length and Spacing of Electrodes. The design of the electrodes is critical for determining the instantaneous power available at their output. For most applications, we prefer to use a fixed length (14 cm) and spacing (4 cm) of electrodes as they were more convenient to install than longer electrodes. Figure 6 shows the charge time and incoming power for different lengths of electrode and Figure 7 charge time and incoming power for different separation distances between the two electrode. It shows how charge time reduces with increased length and separation of electrodes. Here location A corresponds to the ground floor of cement office building having tile floor and location B corresponds to the fifth floor of the same building having carpet surface.

6.2.2 Size of Storage Capacitor. We compute the capacitor required for each application according to the net energy required and equate this to the amount of energy discharged from the storage capacitor using Equation 2.

$$E_{req} \leq E_{dis} = \frac{1}{2} * C_{store} * (V_{init}^2 - V_{final}^2) \tag{2}$$

Consider a sensor that periodically measures temperature. A CC1350 MCU requires 2 V and consumes ~10-12 mA of current for taking one temperature measurement and transmitting this data over a sub-GHz radio. This entire process takes approximately 10 ms. Details specific to this application are discussed in Section 7. We use a high-side switch (Semtech TS12001) with a hysteresis window of 500 mV so we can discharge the storage capacitor by only 500 mV. As this application requires 2 V, we use a high-side switch with a threshold voltage of 1.8 V and a turn on voltage of 2.21 V. We compute energy required for this application as

$$\begin{aligned} E_{req} &= V * I * T \\ &= 2V * 0.012A * 0.010s = 240\mu J \end{aligned} \tag{3}$$

Next we compute the value of the storage capacitor using Equation 2:

$$C_{store} = \frac{2 * E_{dis}}{(V_{init}^2 - V_{final}^2)} \tag{4}$$

In this case, the turn-on voltage of the high-side switch (V_{init}) is 2.11 V and the lower threshold of the high-side switch (V_{final}) is 1.8 V. E_{dis} can be equated to E_{req}, but ideally should be greater than E_{dis}. From Equation 4, we compute value of storage capacitor as 292.68 µF. However, the nearest available capacitor value with low DC leakage is 330 µF (AVX TAJC337K004RNJ), which can facilitate an energy budget of 270.6 µJ. Similarly, we can select the storage capacitor size based on the application's energy budget. Note that the time required to store energy on the capacitor will depend on the length of electrodes as the instantaneous power would vary with the length of the harvesting electrodes. Figure 8 shows the charge time and incoming power for different capacitors size.

6.2.3 Configuration of the Charge Control Circuit. The threshold voltage of the high-side switch is the third design variable which controls the output voltage of this harvester. For sparse sensing applications, the discharge time from V_{init} to V_{final} is a few ms and the average voltage output is around $(V_{init} + V_{final})/2$. For most of the applications, we rely on a high-side switch that has a threshold voltage of 1.8 V and turn on voltage of 2.21 V as it can serve most of the sensing applications unless they require greater than 2 V on an average. For applications which require more than a 2 V input, like sensing environmental parameters or powering a time-lapse camera, we use a high-side switch with a threshold of 3 V and a turn-on voltage of 3.5 V which can provide an average voltage of 3.25 V. For sparse sensing applications which do not have any timing constraints for sensing, we only vary these three design parameters. However, apart from these three design variables, we optionally add a timer (Texas Instruments TPL5110) controlled MOSFET driver (IRLML6402) for specific applications which require a continuous or event-based power draw. This timer can be programmed to the drive output load in a periodic manner for a known duration, thus facilitating continuous sensing by delivering a small amount of energy after a known time interval.

7 APPLICATION SPACE

In order to demonstrate the applicability of this capacitive energy harvester, we developed three different applications: appliance state (on/off) monitoring for energy sustainability; sensing environmental parameters like

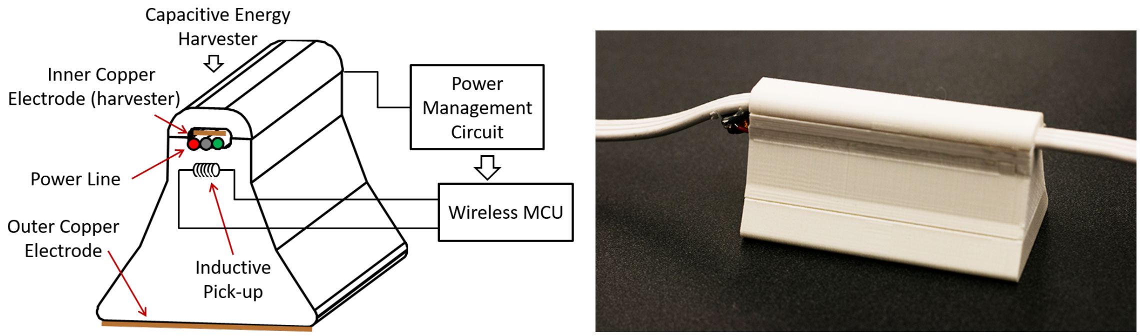

Fig. 9. (a) Block diagram of ApplianceTag showing inductive pick-up for sensing appliance state(on/off) and capacitive electrodes for energy harvesting (b) plot showing appliance state information (on/off) measured using ApplianceTag along with ground truth data from collected using current transformer

temperature, humidity, and light intensity for indoor vertical farming applications; and distributed temperature sensing inside buildings for HVAC control. Each of these applications requires optimization of certain design parameters of the CapHarvester in order to facilitate a variable energy budget.

7.1 ApplianceTag

ApplianceTag, an exciting application of CapHarvester, allows for non-invasive stick-on appliance state monitoring. It uses an inductive pick-up (Bourns SDR1806-102KL[5]) connected to an ADC (CC1350) to detect appliance state (on/off) using stray magnetic fields present around power cords. This approach to appliance state sensing is based on work by Rowe et al. [15]. Intuitively, as per KCL, one expects the net magnetic field present around multi-wire power cables with phase, neutral and earth wires bundled together to be zero. However, depending on the position of the inductive pick-up around a wire bundle and the bundle's asymmetry, stray magnetic fields, albeit with low SNR, can be sensed. In our application, this is sufficient to detect loads of approximately 500 W. We note that with an appropriate low power amplifier, we can significantly lower this detection threshold.

Key features of the ApplianceTag include:

- Can be installed on any power line with no ohmic connection for appliance state monitoring and for energy harvesting.
- Can harvest energy even when appliance is not active or drawing any current.
- Does not require a junction box for installation and can go behind walls for infrastructure mediated sensing.

Once the storage capacitor reaches a certain threshold (2.21 V in this case), the CC1350 wireless MCU turns on, which is programmed to immediately take 56 ADC samples at a sampling rate of 3.360 kHz. These parameters were chosen to ensure that an entire 60 Hz AC cycle is captured. Next, the signal is de-meaned and the signal energy is computed. This value is transmitted back to a base station over an RF link. A threshold is used to detect the appliance ON/OFF state followed. This application requires an energy budget of 250 μJ, which is facilitated by the use of a 330 μF storage capacitor. In our testing, this resulted in an average duty cycle of 1 transmission every 13 minutes. Figure 9(a) shows the block diagram of ApplianceTag. We tested this scenario by monitoring the

[5]http://www.bourns.com/docs/Product-Datasheets/SDR1806.pdf

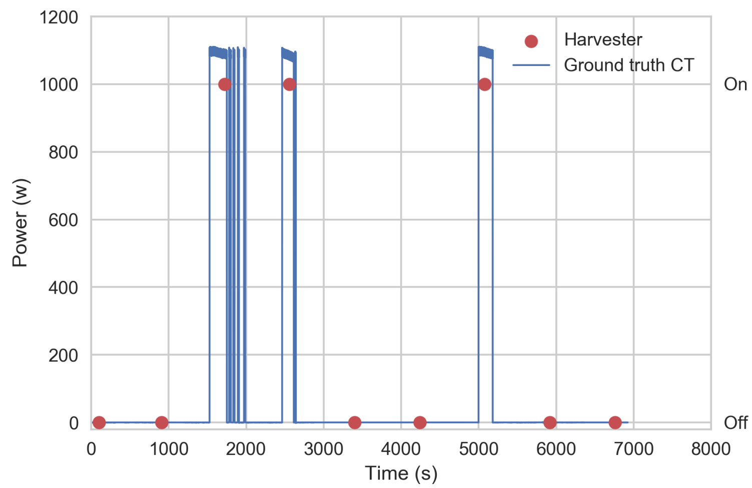

Fig. 10. Plot showing appliance state information (on/off) for a 1 kW hot plate measured using ApplianceTag along with ground truth data from collected using current transformer

state of a 1 kW hot plate, which was manually turned on and off. We compare our data against ground truth data collected using a current transformer(CR3100) for two hours[6] in Figure 10.

7.2 HeatMap

In this application, distributed temperature across a building is gathered to create an hourly heat map of the building. Most building managers perform temperature logging on an hourly basis for fine grained control of heating ventilation and air-conditioning (HVAC) systems. HVAC, being the most energy-expensive load in any commercial or residential building, requires indoor temperature sensing for an effective scheduling of different zones. This requires putting temperature loggers in each and every zone and as the deployment scales, keeping track of batteries becomes a challenging job. We alleviate this by enabling temperature sensing powered by the capacitive energy harvester connected to power lines that are close to air handling units (AHUs). For this application, we chose a 220 uF storage capacitor which results in an average transmission every 6 min with a standard capacitive electrode (14 cm long with a 4 cm separation between electrodes).

Figure 12 shows the temperature variation logged using an on-chip (TI CC1350) temperature sensor powered via the capacitive harvester along with the ground truth data logged using a high resolution temperature sensor (Texas Instruments HDC1000YPA[7])

[6] http://www.crmagnetics.com/Assets/ProductPDFs/CR3100.pdf
[7] http://www.ti.com/lit/ds/symlink/hdc1000.pdf

Fig. 11. A possible implementation of a temperature monitor deployed on a stud (location E)

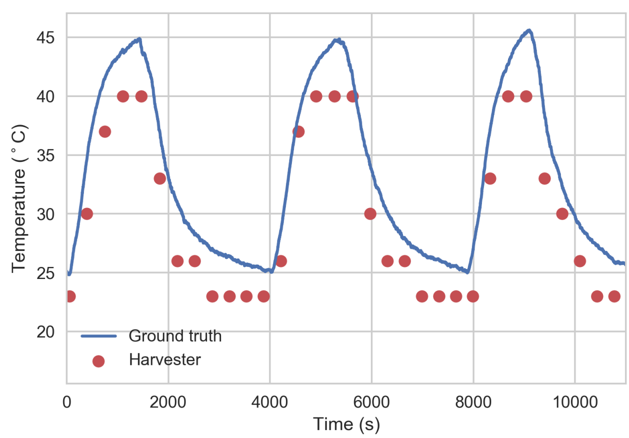

Fig. 12. Temperature variation logged using on-chip (TI CC1350) temperature sensor powered using capacitive harvester along with the ground truth data logged using high resolution temperature sensor (Texas Instruments HDC1000YPA)

7.3 FarmCheck

FarmCheck demonstrates sensing environmental parameters like temperature, humidity, and light intensity for indoor vertical farming applications. We make use of the Texas Instruments CC1350 SensorTag[8] platform for this application. SensorTag is a development board that is fitted with ten different ambient sensors including high resolution temperature (TMP007), humidity (HDC1000YPA), and light sensors (OPT3001). In contrast to previous applications, FarmCheck requires the most power and a 3 V power supply for operation. These requirements were met by designing a circuit that employs a high-side switch with a threshold voltage (V_{th}) of 3 V and a 660 µF storage capacitor resulting in being able to produce 1072 µJ. On an average, this results in a RF transmission every 27 minutes.

Figure 13 shows the temperature, humidity, and light intensity variation for 36 hrs of a kitchen garden. Figure 1 (right) shows a possible implementation of this scenario.

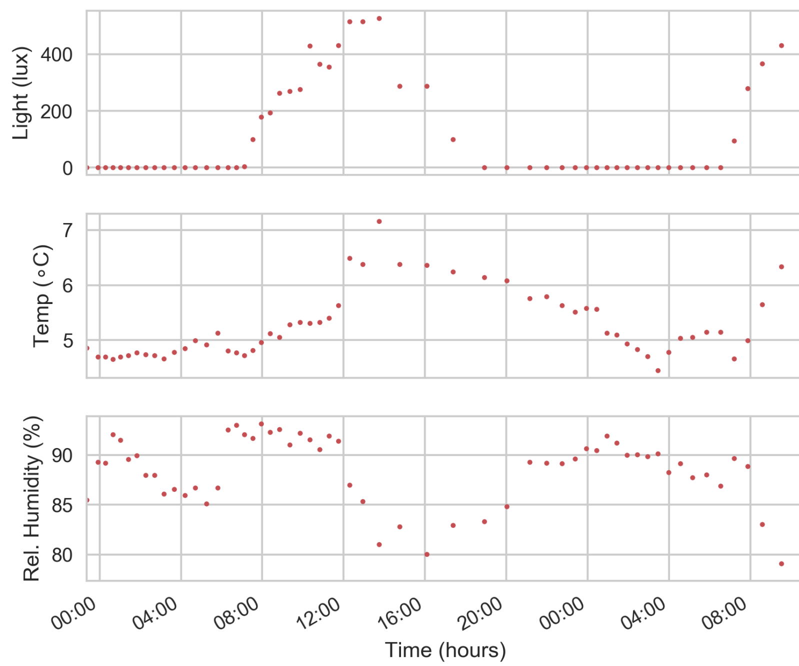

Fig. 13. Environmental parameters logged by our harvester and wirelessly streamed to a base station over a period of over 36 hours.

8 DISCUSSION

Previous capacitive energy harvesters using stray electric fields have required a direct (ohmic) connection to earth ground which has severely limited their applications on low voltage AC power lines. In this work, we have proposed a stick-on capacitive energy harvester that does not require an ohmic connection to earth ground and generates a local reference ground using stacked capacitive electrodes. Our experiments demonstrate that our

[8]https://www.mouser.com/publicrelations_ti_cc1350_devkits_2016final/

device can harvest 270.6 μJ of energy in 12 min. We also demonstrate several applications, such as distributed temperature monitoring, appliance state monitoring, and environmental parameter logging for indoor farming.

8.1 Study Limitations

The experiments performed in the residential setting involved environments with variable humidity; the attic, garage, and house had humidities of 63%, 39%, and 30% respectively. We hypothesize that higher humidity increases the harvesting potential of our system. As an environment becomes more humid, the material of the floor and walls become more wet, which improves their coupling to earth's ground.

Our study was only conducted in the United States. North American AC power lines operate at 110V, while AC power lines in other regions operate at 230V (Asia-Pacific) and 220-240V (Europe). Although we have done all the experiments with 110 V AC power lines, our same electronic design can also be used with 220 V AC power lines since the reverse voltage of the diodes in the rectifier bridge is high enough. Also, the junction capacitance of these diodes supports the range of frequencies available in other countries. If someone wants to use our design for more HV power lines, they need to customize the layout of harvesting electrodes a bit to ensure that voltage output from capacitive harvester along with the available earth ground is enough to sustain the DCL of storage capacitors, i.e.,>10-12V. Also, the output of electrodes should be less than the maximum reverse voltage of these diodes. The stray electric field generated on the outer surface of the power line is proportional to the magnitude of the alternating voltage fed through the power line, so the capabilities of this harvester will scale up in regions with AC power lines that have higher voltage ratings.

8.2 Hardware Limitations

Our proposed capacitive energy harvester relies on the local reference ground generated by the stacked capacitive electrodes and relies weakly on coupling with the earth ground available through nearby metallic or concrete structures. Our harvester under performs in certain scenarios when there is a huge air gap between earth ground and the local reference (outer electrode of harvester). Since air is the worst dielectric possible (ϵ_r=1.0), the gap provides negligible coupling to earth ground and the outer electrode becomes a floating electrode. Our harvester struggles to collect energy in scenarios where power lines are dangling in the air or do not have any surface in contact with them. For example, our harvester is less effective on a table with wooden legs than it is on a shelf with vertical boards.

8.3 Unexplored Applications

We outlined three different application categories for our harvester - sparse, continuous, and event-based - but our evaluation focuses on three different sparse sensing applications. We informally evaluated a continuous sensing application on a breadboard where a timer based MOSFET driver is connected on the output of the high-side switch. The setup included an ADC (MSP430) that was triggered by a timer-based MOSFET driver every 5 minutes. We found that taking each ADC sample and writing it to FRAM consumes 20 μJ of energy. These results to do not translate to real-world applications given the controlled setup and different grounding; however, we were encouraged by these results. Our harvester can collect 270.6 μJ in 12 minutes (across a 330 μF storage capacitor), which is more than enough given our informal results. Hence, we can enable applications which sample data every minute and do delayed transmission by computing the appropriate size of the storage capacitor to do a transmission every 12 or 24 hours. Similarly, we can enable event-based sensing by adding soft constraints on continuous sensing and enable an event-based transmission, such as an occupancy sensor or pressure gauge trigger.

9 CONCLUSION

The increase of smart devices due to the popularity of Internet of Things applications demands devices that can operate without the need for frequent battery maintenance. To support battery-free applications, we propose a novel battery-free, stick-on capacitive energy harvester that harvests the stray electric field generated around AC power lines without a reference connection to earth ground. Our harvester also does not require an active load on the power line, making it more widely applicable and easier and safer to deploy. Our controlled lab measurements and real-world deployments demonstrate that our device can harvest 270.6 μJ of energy from a 14 cm long interface in 12 min. We foresee a number of possible applications, ranging from sparse sensing of temperature in houses to event-driven appliance state monitoring. We plan to improve upon our initial designs and make them work in other countries as well. We also look forward to other researchers and engineers doing the same.

A TERMINOLOGY USED

C_{pp} = Primary capacitance between the phase wire conductor and the outer surface of power cable
C_{pn} = Primary capacitance between the neutral wire conductor and the outer surface of power cable
C_{pg} = Primary capacitance between the ground wire conductor and the outer surface of power cable
C_s = Secondary capacitance between the ground wire conductor and the outer surface of power cable
V_{final} (or V_{th}) = Lower threshold voltage of the high-side switch
V_{init} = Turn-on voltage of high-side switch
C_{store} = Capacitance of storage capacitor used for energy harvesting
E_{dis} = Energy that can be faciliated (discharged) through storage capacitor
E_{req} = Energy required for any specific application of CapHarvester

ACKNOWLEDGMENTS

The authors would like to thank Prof. Joshua Smith (Sensor Lab, UW) and his student Saman Naderiparizi for providing technical guidance and support at various times during this project. We would also like to thank Gabe A. Cohn (MSR, Redmond) and Edward J. Wang (Ubicomp Lab, UW) for participating in technical discussions during this project. Finally, we would like to acknowledge Department of Science and Technology, Govt. of India for providing support to the corresponding author through IUSSTF BHAVAN Fellowship 2017 (BHAVAN 2017/Internship/3/) and TCS Research for delivering Ph.D. Fellowship to the corresponding author.

REFERENCES

[1] G Asada, M Dong, TS Lin, F Newberg, G Pottie, WJ Kaiser, and HO Marcy. 1998. Wireless integrated network sensors: Low power systems on a chip. In *Solid-State Circuits Conference, 1998. ESSCIRC'98. Proceedings of the 24th European*. IEEE, 9–16.

[2] Bradford Campbell and Prabal Dutta. 2014. Gemini: A non-invasive, energy-harvesting true power meter. In *Real-Time Systems Symposium (RTSS), 2014 IEEE*. IEEE, 324–333.

[3] Keun-Su Chang, Sung-Muk Kang, Kyung-Jin Park, Seung-Hwan Shin, Hyeong-Seok Kim, and Ho-Seong Kim. 2012. Electric field energy harvesting powered wireless sensors for smart grid. *Journal of Electrical Engineering and Technology* 7, 1 (2012), 75–80.

[4] Samuel DeBruin, Bradford Campbell, and Prabal Dutta. 2013. Monjolo: An energy-harvesting energy meter architecture. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*. ACM, 18.

[5] Samuel DeBruin, Branden Ghena, Ye-Sheng Kuo, and Prabal Dutta. 2015. Powerblade: A low-profile, true-power, plug-through energy meter. In *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*. ACM, 17–29.

[6] Vikram Gupta, Arvind Kandhalu, and Ragunathan Raj Rajkumar. 2010. Energy harvesting from electromagnetic energy radiating from AC power lines. In *Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors*. ACM, 17.

[7] Joseph M Kahn, Randy H Katz, and Kristofer SJ Pister. 1999. Next century challenges: mobile networking for âĂIJSmart DustâĂİ. In *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*. ACM, 271–278.

[8] S Kang, S Yang, and H Kim. 2017. Non-intrusive voltage measurement of ac power lines for smart grid system based on electric field energy harvesting. *Electron. Lett* 53, 3 (2017), 181–183.

[9] Hoseong Kim, Dongkil Choi, Sungmin Gong, and Kyungjin Park. 2014. Stray electric field energy harvesting technology using MEMS switch from insulated AC power lines. *Electronics letters* 50, 17 (2014), 1236–1238.

[10] Jing-Quan Liu, Hua-Bin Fang, Zheng-Yi Xu, Xin-Hui Mao, Xiu-Cheng Shen, Di Chen, Hang Liao, and Bing-Chu Cai. 2008. A MEMS-based piezoelectric power generator array for vibration energy harvesting. *Microelectronics Journal* 39, 5 (2008), 802–806.

[11] Jinyeong Moon, John Donnal, Jim Paris, and Steven B Leeb. 2013. VAMPIRE: A magnetically self-powered sensor node capable of wireless transmission. In *Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE*. IEEE, 3151–3159.

[12] Michael J Moser, Thomas Bretterklieber, Hubert Zangl, and Georg Brasseur. 2011. Strong and weak electric field interfering: Capacitive icing detection and capacitive energy harvesting on a 220-kV high-voltage overhead power line. *IEEE Transactions on Industrial Electronics* 58, 7 (2011), 2597–2604.

[13] Matthai Philipose, Joshua R Smith, Bing Jiang, Alexander Mamishev, Sumit Roy, and Kishore Sundara-Rajan. 2005. Battery-free wireless identification and sensing. *IEEE Pervasive computing* 4, 1 (2005), 37–45.

[14] Vijay Raghunathan, Aman Kansal, Jason Hsu, Jonathan Friedman, and Mani Srivastava. 2005. Design considerations for solar energy harvesting wireless embedded systems. In *Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on.* IEEE, 457–462.

[15] Anthony Rowe, Mario Berges, and Raj Rajkumar. 2010. Contactless sensing of appliance state transitions through variations in electromagnetic fields. In *Proceedings of the 2nd ACM workshop on embedded sensing systems for energy-efficiency in building*. ACM, 19–24.

[16] Faisal Karim Shaikh and Sherali Zeadally. 2016. Energy harvesting in wireless sensor networks: A comprehensive review. *Renewable and Sustainable Energy Reviews* 55 (2016), 1041–1054.

[17] Henry A Sodano, Garnett E Simmers, Remi Dereux, and Daniel J Inman. 2007. Recharging batteries using energy harvested from thermal gradients. *Journal of Intelligent material systems and structures* 18, 1 (2007), 3–10.

[18] Vamsi Talla, Bryce Kellogg, Benjamin Ransford, Saman Naderiparizi, Shyamnath Gollakota, and Joshua R Smith. 2015. Powering the next billion devices with wi-fi. In *Proceedings of the 11th ACM Conference on Emerging Networking Experiments and Technologies*. ACM, 4.

[19] Yen Kheng Tan and Sanjib Kumar Panda. 2011. Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless sensor nodes. *IEEE Transactions on Industrial Electronics* 58, 9 (2011), 4424–4435.

[20] Xudong Wang. 2012. Piezoelectric nanogeneratorsâĂŤharvesting ambient mechanical energy at the nanometer scale. *Nano Energy* 1, 1 (2012), 13–24.

[21] Daniel J Yeager, Alanson P Sample, Joshua R Smith, and Joshua R Smith. 2008. Wisp: A passively powered uhf rfid tag with sensing and computation. *RFID handbook: Applications, technology, security, and privacy* (2008), 261–278.

[22] Hubert Zangl, Thomas Bretterklieber, and Georg Brasseur. 2008. Energy harvesting for online condition monitoring of high voltage overhead power lines. In *Instrumentation and Measurement Technology Conference Proceedings, 2008. IMTC 2008. IEEE*. IEEE, 1364–1369.

[23] Hubert Zangl, Thomas Bretterklieber, and Georg Brasseur. 2009. A feasibility study on autonomous online condition monitoring of high-voltage overhead power lines. *IEEE Transactions on Instrumentation and Measurement* 58, 5 (2009), 1789–1796.

[24] Chen Zhao, Sam Yisrael, Joshua R Smith, and Shwetak N Patel. 2014. Powering wireless sensor nodes with ambient temperature changes. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 383–387.

Received February 2018; revised July 2018; accepted September 2018